“Effect of Chemistry and Processing Variables on the Mechanical Properties of Thin-wall Ductile iron castings”

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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BY
Susanta Kumar Swain
Roll No: 60604001

Under the guidance of
Dr.Sudipta Sen
Asst. Professor
Department of Metallurgical & Materials Engineering
N.I.T-Rourkela

NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA – 769008

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Date:

Place: NIT, Rourkela

Susanta Kumar Swain

M.Tech. (Res)

Roll No: 60604001

NIT, Rourkela

Department of Metallurgical and Materials Engineering

CERTIFICATE

This is to certify that the work in this thesis Report entitled "Effect of chemistry & processing variables on the mechanical properties of Thin-Wall Ductile Iron Casting" *which is being submitted by Mr. Susanta Kumar Swain of Master of Technology (Res), (Roll No: 60604001) National Institute of Technology, Rourkela has been carried out under my guidance and supervision in partial fulfillment of the requirements for the degree of* Master of Technology(Res.) *in Metallurgical and Materials Engineering and is bonafide record of work.*

Dr.Sudipta Sen
Asst.Professor
Deptt.of metallurgical & materials Engg.
NIT, Rourkela

Date:
Place : NIT, Rourkela

ABSTRACT

Cast iron is an alloy of iron containing more than 2% carbon as an alloying element. It has almost no ductility and must be formed by casting. Ductile iron structure is developed from the melt of cast iron. The presence of silicon in higher amount promotes the graphitization, inhibiting carbon to form carbides with carbide forming elements present. The carbon forms into spheres when Ce, Mg are added to the melt of iron with very low sulphur content. Due to this special microstructure containing graphite in nodular form ductile iron possesses ductility & toughness superior to that of any cast iron & steel structure resulting in numerous successes in industrial application. Ductile iron castings with 3 and 12 mm thickness with varying chemical composition were cast in furan resin sand molds to identify the effect of sample thickness on microstructural changes and selected mechanical properties. The effect of melt chemistry and molten metal processing variables (i.e., pre-conditioning of the base iron, inoculation type and practice, and pouring temperature, etc.) on the tensile and impact properties of thin-wall ductile iron castings has been investigated. Comparison of 3 and 12 mm sections within the same casting showed that section size was the main factor influencing tensile properties of ductile irons. While many samples from 3 mm sections showed low elongation values, likely caused by a high pearlite content or presence of carbides, many others showed higher elongations and superior strengths well above those required in ASTM A536 grades. At moderate to high elongations, the thin-wall samples were significantly stronger than samples from identical irons of 12 mm section.

A direct comparison between impact values could not be made due to different test specimen sizes, but it is clear that toughness in the two section sizes was roughly equivalent when account was made for the total cross sectional area. The main difference between the Impact properties in the two section sizes lay in the relative insensitivity of the thin-section specimens to either melt chemistry or molten metal processing variables. Of the elements contained in the iron, silicon had the greatest effect on the tensile properties of the thin-wall sections. The same increase in silicon content of the thin-wall sections had little effect on impact toughness. As expected, any processing variable that led to an increase in nodule count (with a corresponding increase in ferrite content) led to greater ductility, lower strength, and improved toughness. Of the

variables studied the greatest effect was found to be from late inoculation, base iron pre-conditioning, and the use of an inoculant containing bismuth and rare earths.

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Chapter 1

Introduction to Ductile Iron

1.0 Introduction

Ductile Iron also referred to as nodular iron or spheroidal graphite iron was patented in 1948.After a decade of intensive development work in the 1950s, ductile iron had a phenomenal increase in use as engineering material during 1960s, and the rapid increase in commercial application continues today.

Ductile iron as a technologically useful material has been employed for a score of years .During this period while many investigators have examined its mechanical performance under a wide range of conditions others have attempted to explain its solidification behavior and the many variables which intervene in producing an acceptable product. Yet even at this date we are still at a loss to explain in a fundamental way how an otherwise flakelike graphite shape develops in to the spheroidal morphology which gives ductile iron its superior properties.

An unusual combination of properties is obtained in ductile iron because the graphite occurs as spheroids rather than flakes as in grey iron. This mode of solidification is obtained by adding a very small but specific amount of Mg or Ce or both to molten iron of a proper composition. The base iron is severely restricted in the allowable contents of certain minor elements that can interfere with the graphite spheroid formation. The added Mg reacts with S and O in the molten iron and change the way the graphite is formed .Control procedures have been developed to make the processing of ductile iron more effective.

The high carbon and silicon content of ductile iron provide the casting process a few advantages, but the graphite spheroids have only a nominal influence on the mechanical properties of the metal. Ductile iron like malleable iron exhibits a linear stress-strain relation, a considerable range of yield strengths and its name implies ductility. Castings are made in a wide range of sizes with sections that can be either very thin or very thick.

The different grades are produced by controlling the matrix structure around the graphite either simply by casting or by subsequent heat treatment. Only minor compositional differences exist among the regular grades and these adjustments are made to promote the desired matrix microstructures. Alloy additions may be made to ductile iron with a view to control the matrix structure (as-cast) in order to provide response to heat treatment. Special analysis of ductile irons and high alloy ductile irons can provide unusual properties for special applications.

Reducing the weight of ductile iron castings (i.e., producing thin-section ductile iron castings) is an important method for saving energy and material. Let us take an automobile for example: a reduction of 100kg in weight saves 0.5 liter of petrol per 100km driven [3]. So many metallurgical workers are dedicating themselves to developing and perfecting thin-section ductile iron casting technology [4].Thin-section ductile iron castings tend to develop a white or mottled structure and micro porosity during solidification, which can strongly affect the mechanical properties and machinability. It is well known that these defects are significant in the solidification morphology of the castings.

In recent years, there has been a clear tendency towards weight reduction on manufacturing mechanical parts in order to reduce costs. In the case of transport industry, this is done also for environmental reasons. When considering thin wall parts, the higher surface to volume ratio makes surface properties essential for part quality and service performance, particularly when such parts are to be used in corrosive environments. Ductile iron has recently been used in thin wall parts. For traditional casting operations, wall thickness reduction implies an increase in the cooling rate and, consequently, microstructural changes. The increase in nucleation rate leads to an increase in the number of graphite nodules, a decrease in grain size and changes in the segregation profile.

1.1 Historical background

A new engineering material was born in 1948 with the announcement [1,2] at the 1948 AFS castings congress that small additions of certain elements resulted in the formation of spheroidal graphite in as-cast iron .The independent studies in England at the British Cast Iron Research Association using cerium additions [1] and the United states at the International Nickel Company using magnesium additions [2] demonstrated the dramatic effect of these elements on promoting the formation of a spheroidal rather than a flake, graphite morphology during solidification. This spheroidal graphite morphology-developed during solidification –is the key factor responsible for the unique mechanical and physical properties of ductile iron .This was the culmination of an exciting period of research and initiated an era of one of the most dramatic commercial developments in the metals world.

It is well known that the production of ferrous castings predates biblical times, but very slow advances in the art were made over the several thousands of years involved. Not until the science of metallurgy began to make significant advances around the start of the 20^{th} century did the curve really turn upward. The metallurgists then began seriously to study the effect of variations in composition, melting procedures, solidification characteristics, cooling rates, processing variables and many other parameters. Effects were being made to correlate strength to size, amount, shape, distribution of graphites and methods of influencing these factors were being developed. However, the technical literature were completely silent regarding i) a cast iron having it's graphite in the spheroidal form in the as-cast condition or ii) a high carbon of any type exhibiting ductility in the as-cast condition.

One of the materials to be born in this era and which was being promoted in the 1930s was an abrasion white cast iron with high hardness which results from a martensite-carbide matrix promoted by Ni and Cr contents nominally 4.5 & 1.5% respectively. This material or family of materials still produced in large quantities all over the world for grinding mill balls,plates,rolls and many applications requiring outstanding abrasion resistance .It is a product well known in Australia and very likely will enjoy a sizable growth in view of the huge mining potential . After 2^{nd} world war, Cr appeared to one of the elements that would become scarce and without it, white cast would be less carbidic, considerably softer and hence lacking in the desired abrasion resistance.

To meet such eventually, research laboratories all over the world seek a substitute element of a Cr as a carbide former in martensitic white cast iron. Necessarily, the element have to satisfy all the three conditions i.e. be plentiful, on critical to the war effort and be required in small amount .All the metallic and semi metallic elements which were known to combine chemically with carbon to form carbide were tested. Among these was Mg. Further it was believed by the investigators that the solubility of Mg in ferrous materials was exceeding low. The addition of Mg was the sole purpose of deoxidation ,evidently with no desire or hope of retaining in the iron .The addition of Mg to the base iron exhibited unusual toughness by resisting fracture where as other broke in usual brittle manner. It was latter learnt an analytical method to determine Mg in cast iron. It is known that Mg is retained in iron & in instance to more than 1%.

The next step obviously to investigate the effect of Mg on simple grey cast iron and such a research programme was started early in 1943. The grey cast iron was treated with various amounts of Mg as 80%, Ni-20% Mg alloy upto a minimum of 0.3%. An examination of microstructure showed that refinement of flake graphite had occurred. The obvious next step was larger addition of Mg. There was much excitement in the laboratory when the heats were tested, for the results lead to the realization that it was not merely an improvement in cast iron that had been achieved, but rather creation of a completely new product .The tensile strength has increased to unexpected level. An immediate examination under microscope revealed that the graphite was not present as flake but as well dispersed spheroids. With a small, but effective amount of Mg produced high strength spheroidal graphite cast iron as well as with good mechanical properties.

1.2. Birth of Ductile Iron

In spite of the progress achieved during the first half of 20th century in the development of grey and malleable irons, foundry men continued to search for the ideal cast iron-an as-cast “grey iron” with mechanical properties equal or superior to malleable iron. J.W.Bolton, speaking at the 1943 convention of the American Foundry men’s Society (AFS), made the following statements.

“Your indulgence is requested to permit the posing of one question. Will real control of graphite shape is realized in grey iron? Visualize a material, possessing (as-cast) graphite flakes or groupings resembling those of malleable iron instead of elongated flakes”.

A few weeks later, in the International Nickel Company Research Laboratory ,Keith Dwight Millis made a laddle addition of magnesium (as a copper magnesium alloy) to cast iron and justified Bolton’s optimism-the solidified castings contained not flakes, but nearly perfect spheres of graphite. Ductile Iron was born!

Five years later, at the 1948 AFS Convention, Henton Morrogh of the British Cast Iron Research Association announced the successful production of spherical graphite in hypereutectic gray iron by the addition of small amounts of Cerium.

At the time of Morrogh's presentation, the International Nickel Company revealed their development, starting with Milli's discovery in 1943, of magnesium as a graphite spherodizer. On October 25, 1949, patent 2,486,760 was granted to the International Nickel Company, assigned to Keith D. Millis, Albert P.Gegnebin and Norman B.Pilling. This was the official birth of ductile iron, the beginning of 40 years of continual growth worldwide, in spite of recessions and changes in materials technology and usage.

The US transport industry faced three major challenges: reduce emission, improve fuel economy and lower cost. One method of improving fuel economy is to reduce vehicle weight. In 1970's, the automotive industry reduced vehicle weight by reducing the thickness of the steel sheet (driving the development of high-strength low- alloy steels and corrosion resistant coatings). In the 1980's and the early 1990's, vehicle weight was further reduced by substituting aluminum for cast iron and steel (primarily in cylinder heads, engine blocks and wheels). Currently the substitution of aluminum for cast iron and steel, and magnesium is continuing. The use of aluminum, however, results in higher vehicle costs, which are passed on to the consumer. To provide the transport industry with a means of weight reduction at little or no cost penalty, the cast iron and

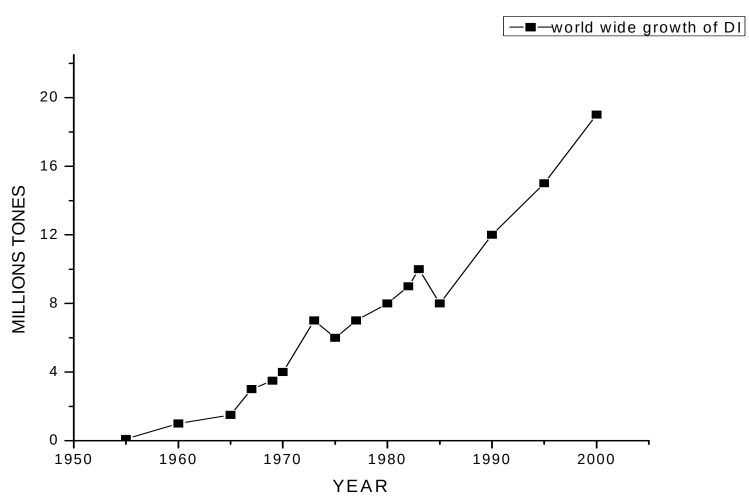


Fig.1: Worldwide growth of ductile iron production, 1950-2000, BTM Consult, March-2000

Steel industries have undertaken major product improvement programs.e.g. thin-wall iron casting technology and light weight steel body technology. Recent research (Javaid, 1999; Javaid, 2000; Labreccque, 2000) has shown the feasibility of producing thin-wall iron castings. Commercially viable, light weight cast iron technology is being developed by TWIG (Thin-wall Iron Group) through a co-operative program with major US foundry companies, foundry suppliers, the Big three automakers, the University of Alabama, and U.S. Department of Energy Albany Research center. TWIG has launched programs specifically focused on control of microstructure, solidification modeling, process variability, and dimensional capability in thin section castings, generation of useful mechanical data.

1.3. Modern Trends

During the first 20 years of SG iron production; there have been many significant changes in foundry equipment, materials & practices. The development & growth of many of these related directly to improve the process of producing SG iron and now the production of good quality SG iron is a routine affair. All are more familiar with these changes which include the development of basic cupola, the water cooled cupola, the commercial development of shell molding, alloys and devices for treating the iron, to a new fame. In Europe, induction furnace melting gained popularity because of the more precise control if afforded for composition and temperature plus the fact that a wide variety of charge materials could be used. In the early 1960s interest in electric arc furnace melting spread to other parts of the world. It facilitated a finer degree of quality control in meeting the veer increasing by rigid demands put on castings.

Designer Engineers can now optimize casting shape and performance with increased speed and confidence. Recent development in CAD/CAM, solid modeling and finite element analysis (FEA) techniques permits highly accurate analysis of stress distributions and component deflections under simulated operating conditions, In addition to enhancing functional design, the analytical capabilities of CAD/CAM have enabled foundry engineers to maximum casting integrity and reduce production costs through the optimization of solidification behavior.

Castings offer cost advantages over fabrications and forgings over a wide range of production rates, component size and design complexity. The mechanization and automation of castings process have substantially reduced the cost of high volume castings, while new and innovative techniques such as the use of Styrofoam patterns and CADA/CAM pattern production have dramatically reduced both development times and costs for prototype and short-run castings. AS confidence in FEA techniques increases, the importance of prototype, often in the form of fabrications which “compromise” the final design, will decrease and more new components will go directly from the design stage to the production castings.

Nowadays the automotive, wind power and agriculture implement industries are major users of ductile iron castings. Automotive castings requirements represent approximately 55 percent of the total worldwide ductile iron casting production. The rapid growth of ductile iron industries and the high annual utilization of ductile iron castings are testimonials to the out standings mechanical properties, quality and economics of ductile iron castings. The fact that ductile iron castings are used for such critical automotive applications as crankshafts, front wheel spindle supports, and connecting rods is a further testimonial to the high reliability and process economics associated with ductile iron castings.

1.4. It’s Development & Future

The year 1959 marked the start of rapid growth in the demand for casting and the ensuing annual increases in production were almost phenomenal. Various attempts were made to determine the industrial distribution of spheroidal graphite iron castings. Difficulties arise from the fact that the utilization of the materials varies in different parts of the world. For example, pipes account for about 26% of the production in US, in Japan on the other hand, it accounts for about 70% of the production. In US, three industries consume the major share of the production. Automotive applications take about 40%, pipes 26% and agriculture implements something in excess of 5%. This is probably similar to the situation existing in the rest of the world. However, someone would be very hard pressed to find an industry which did not make use of some spheroidal graphite cast iron, either directly or indirectly. The first stainless steel was patented in the year 1914, but there were no production figures available for years prior to 1929. It is evident that after 16 years, the patent was issued. The production of stainless steel was low as compared to the production of SG cast iron was patented. In fact, it took stainless steel 47 years to reach the level that SG cast iron reached in sixteen years.

The advantages of ductile iron which have led to its success are numerous, but they can be summarized easily – versatility and higher performance at lower cost. Other members of the ferrous castings family may have individual properties which might make them the material of choice in some applications, but non have the versatility of ductile iron, which often provides the designer with the best combination of overall properties. This versatility is especially evident in the area of mechanical properties where ductile iron offers the designer the option of choosing high ductility, with grades guaranteeing more than 18% elongation, or high strength with tensile strength exceeding 825Mpa.

Nowadays, the development of ductile iron has introduced thin-walled ductile iron (TWDI) as a new improvement, in order to increase the strength to weight ratio and, in consequence, its competitiveness against light alloys. The high cooling rate taking place during solidification of thin wall ductile iron castings, promotes two main changes in the microstructure: (a) the precipitation of iron carbides and (b) an important increase in the nodule count. The use of thin walls (less than 4mm thickness) can increase the nodule count up to 2000 nod/mm^2 [5, 6]. In recent years, there has been a clear tendency towards weight reduction on manufacturing mechanical parts in order to reduce costs or, in the case of transport industry, also for environmental reasons. When considering thin wall parts, the higher surface to volume ratio makes surface properties essential for part quality and service performance, particularly when such parts are to be used in corrosive environments.

1.5. Design Flexibility

The design flexibility offered by the casting process far exceeds that of any other process used for the production of engineering components. This flexibility enables the design engineer to match the design of the component of its function. Metal can be placed where it is required to optimize the load carrying capacity of the part, and can be removed from unstressed areas to reduce weight. Changes in cross-section can be streamlined to reduce stress concentrations. The result is that both initial and lifecycle costs are reduced through material and energy conservation and increased component performance.

A recent study by the National Center for Manufacturing Sciences (NCMS) has shown that in certain machine tool applications, the replacement of fabricated structures by Ductile Iron castings could result in cost savings of 39-50%. Commenting on the NCMS study, Mr. Gary Lunger, president of Erie Press Inc. stated:

“We make huge presses and we have relatively clear specifications for what goes into each press. We have been able to use Ductile Iron as a substitute material primarily for cylinders and other parts at a significant cost saving over cast or fabricated steel”.

The sudden arrival of SG cast iron on the material science more than 20 years ego provided a cast iron with spectacularly better properties than grey cast iron and better castability than steel. In times, engineers realized that it was not a single material with one set of properties, rather available at will and capable of serving a wide variety of engineering equipments.

A more interesting area for improved ductile iron lies in the possibility of property improvements of sufficient magnitude to permit a redesign that would result in net reduction in cost for a part, increase life of a part to a degree that the alloy cost would be offset or substantially improve operating economy of mechanical equipment through the ability to operate under much more severe conditions.

The ductile iron castings have served the automotive industry well in many applications since its inception. In recent years there has been an increasing trend towards use of castings. The modern V-8 engine, in which castings are now used for each of the major components, is an example of this trend. In any central foundry project to develop a new casting application, there are two design objects:

First- develop functional characteristics in the castings which are superior to the parts to be replaced.

Second- employ the combination of the parts principle offered by the casting process. The integral ductile iron steering knuckle development met both of the objectives. For the integral ductile iron steering knuckle, the designer has been free to incorporate the requirements of ductile iron and the casting process, as well as combining three parts into one. The result represents a significant improvement over traditional methods of manufacturing steering knuckles due to design flexibility.

Chapter 2

A Brief Discussion about Ductile Iron

2.0. Introduction

"Iron seemeth a simple metal but in its nature are many mysteries"

After three hundred years of progress, the above words of Joseph Glanville are still true. Knowledge is certainly preferable to speculation. And yet, the approach towards solving a given practical problem will be confusing and haphazard without the guidance of ideas on at least what may take place during solidification. Willing or not, one must depend, in part, on hypotheses

Ductile iron is defined as a high carbon containing, iron based alloy in which the graphite is present in compact, spherical shapes rather than in the shape of flakes, the latter being typical of gray cast iron. As ductile iron, sometimes referred to as nodular or spheroidal graphite cast iron, constitutes a family of cast irons in which the graphite is present in a nodular or spheroidal form. The graphite nodules are small and constitute only small areas of weakness in a steel-like matrix. Because of this the mechanical properties of ductile irons related directly to the strength and ductility of the matrix present—as is the case of steels.

The graphite occupies about 10-15% of the total material volume and because graphite has negligible tensile strength, the main effect of its presence is to reduce the effective cross-sectional area, which means that ductile iron has tensile strength, modulus of elasticity and impact strength proportionally lower than that of a carbon steel of otherwise similar matrix structure.

The matrix of ductile irons can be varied from a soft and ductile ferritic structure, through harder and higher strength pearlitic structures to a hard, higher and comparatively tough tempered martensitic or bainitic structure. Thus, a wide range of combinations of strength and ductility can be achieved. General engineering grades of ductile iron commonly have the structures which are ferritic or ferrito-pearlitic. Controlled processing of the molten iron precipitates graphite as spheroids rather than flakes. The round shape of the graphite eliminates the material's tendency to crack and helps prevent cracks from spreading.

Ductile Iron is not a single material, but a family of materials offering a wide range of properties obtained through microstructural control. The common feature that all ductile irons share is the roughly spherical shape of the graphite nodules. These nodules act as “crack arresters” and make ductile iron “ductile”. This feature is essential to the quality and consistency of ductile iron, and is measured and controlled with a high degree of assurance by competent ductile iron foundries. With a high percentage of graphite nodules present in the structure, mechanical properties are determined by the ductile iron matrix.

2.1. Chemical Composition

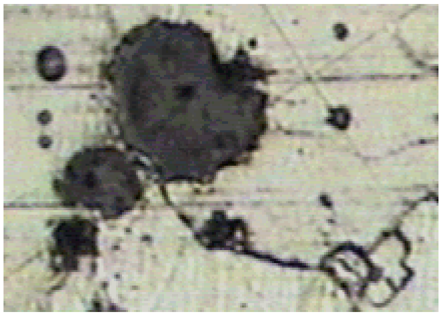
Chemically this material is same as grey iron and is Fe-C-Si alloy. It is one of the more recent developments in cast iron technology has been around since 1948. As the name suggests, it was developed to overcome the brittle nature of grey and white irons. It is also quite ductile in as cast form. The main trace elements present in ductile iron can have a marked influence on the structure and hence the properties of the iron. With the exception of silicon, all elements promote pearlite and all elements with the exception of silicon, nickel and copper also promotes carbides. The strength properties of ferritic ductile iron are generally increased by the elements, which go in to the solution. With the exception of carbon, all the elements increase tensile strength and hardness. An example of the extent to which ferrite is affected by solid solution strengthening is illustrated for the elements silicon and nickel. 1% addition of silicon raises the proof and tensile strength of a ferritic iron by approximately 82 N/mm^2 whereas 1% of nickel increases these properties by 46 N/mm^2. In the ferritic irons increase in tensile strength and proof strength are obtained at the expense of ductility and in such case the iron can become embrittled.

2.2. Structure

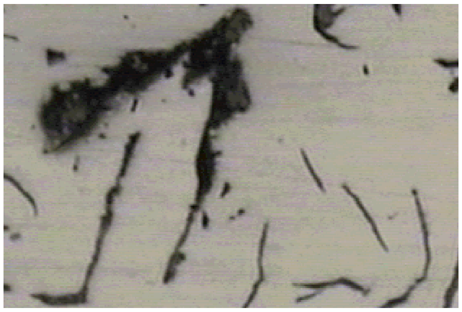
The main difference between ductile iron and grey iron is the morphology of graphite particles which take on a nodular or almost spherical form after suitable treatments are made to the melt. The major microstructural constituents of ductile iron are: the chemical and morphological forms taken by carbon, and the continuous metal matrix in which the carbon and/or carbide are dispersed. The following important microstructural components are found in ductile iron.

2.2.1 Graphite

This is the stable form of pure carbon in cast iron. Its important physical properties are low density, low hardness and high thermal conductivity and lubricity. Graphite shape, which can range from flake to spherical, plays a significant role in determining the mechanical properties of ductile irons. Ductile iron is characterized by having all of its graphite occurs in microscopic spheroids. Although this graphite constitutes about 10% by volume of ductile iron, its compact spherical shape minimizes the effect on mechanical properties. The graphite in commercially produced ductile iron is not always in perfect spheres. It can occur in a somewhat irregular form, but if it is still chunky as Type II in ASTM Standard A247, the properties of the iron will be similar to cast iron with spheroidal graphite. Of course, further degradation can influence mechanical properties. The shape of the graphite is established when the metal solidifies, and it cannot be changed in any way except by remelting the metal. The difference between the various grades of ductile iron is in the microstructure of the metal around the graphite, which is called the matrix. This microstructure varies with composition and the cooling rate of the casting. It can be slowly cooled in the sand mold for a minimum hardness (as-cast) or, if the casting has sufficiently uniform sections, it can be freed of molding sand while still at a temperature above the critical and can be normalized.



(Fig. 2.0)



(Fig. 2.1)

Fig. 2.0, Micrograph of ductile iron showing how graphite spheroids can act as “crack arresters”, and Fig. 2.1, micrograph of gray iron showing crack-like behavior of graphite flakes.)

2.2.2 Ferrite

This is the purest iron phase in a cast iron. In conventional Ductile Iron ferrite produces lower strength and hardness, but high ductility and toughness. In Austempered Ductile Iron (ADI), extremely fine grained acicular ferrite provides an exceptional combination of high strength with good ductility and toughness. The strength properties of ferritic ductile iron are generally increased by the elements, which go in to the solution. With the exception of carbon, all the elements increase tensile strength and hardness. An example of the extent to which ferrite is affected by solid solution strengthening is illustrated for the elements silicon and nickel (Table-5, fig.11a, 11b, 12a).

2.2.3 Pearlite

Pearlite, produced by a eutectoid reaction, is an intimate mixture of lamellar cementite in a matrix of ferrite. A common constituent of cast irons; pearlite provides a combination of higher strength and with a corresponding reduction in ductility which meets the requirements of many engineering applications.

2.2.4 Martensite

Martensite is a supersaturated solid solution of carbon in iron produced by rapid cooling. In the untempered condition it is very hard and brittle. Martensite is normally “tempered”-heat treated to reduce its carbon content by the precipitation of carbides-to provide a controlled combination of high strength wear resistance and ductility.

2.2.5 Austenite

Normally a high temperature phase consisting of carbon dissolved in iron, it can exist at room temperature in austenitic and austempered cast iron. In austenitic irons, austenite is stabilized by nickel in the range of 18-36% [28]. In austempered irons, austenite is produced by a combination of rapid cooling which suppress the formation of pearlite and the supersaturation of carbon during austempering, which depress the start of the austenite-to-martensite transformation far below room temperature.

In austenitic irons, the austenite matrix provides ductility and toughness at all temperatures, corrosion resistance and good high temperature properties, especially under thermal cycling conditions. In austempered ductile iron stabilized austenite, in volume fractions up to 40% in lower strength grades, improves toughness and ductility and response to surface treatments such as fillet rolling.

2.2.6 Bainite

Bainite is a mixture of ferrite and carbide, which is produced by alloying or heat treatment.

2.3 Family of Ductile Iron

With a high percentage of graphite nodules present in the structure, mechanical properties are determined by the ductile iron matrix. The importance of matrix in controlling mechanical properties is emphasized by the use of matrix names to designate the following types of Ductile Iron.

2.3.1 Ferritic Ductile Iron

Graphite spheroids in a matrix of ferrite provide an iron with good ductility and impact resistance and with a tensile and yield strength equivalent to low carbon steel. Ferrite ductile iron can be produced as-cast but may be given an annealing heat treatment to assure maximum ductility and low temperature toughness.

2.3.2 Ferrito- Pearlitic Ductile Iron

These are the most common grade of ductile iron and are normally produced in the as-cast condition. The graphite spheroids are in a matrix containing both ferrite and pearlite. Properties are intermediate between ferritic and pearlitic grades, with good machinability and low production costs.

2.3.3 Pearlitic Ductile Iron

Graphite spheroids in a matrix of pearlite result in an iron with high strength, good wear resistance, and moderate ductility and impact resistant. Machinability is also superior to steels of comparable physical properties.

The preceding three types of Ductile Iron are the most common and are usually used in the as-cast condition, but ductile iron can also be alloyed/or heat treated to provide the following grades for a wide variety of additional applications.

2.3.4 Martensitic Ductile iron

Using sufficient alloy additions to prevent pearlite formation, and a quench-and-temper heat treatment produces this type of ductile iron. The resultant tempered martensite matrix develops very high strength and wear resistance but with lower levels of ductility.

2.3.5 Austenitic Ductile Iron

Alloyed to produce an austenitic matrix, this ductile iron offers good corrosion and oxidation resistance, and good strength and dimensional stability at elevated temperatures.

2.3.6 Austempered Ductile iron (ADI)

ADI, the most recent addition to the ductile iron family, is a sub-group of ductile iron produced by giving conventional ductile iron a special austempering heat treatment. Nearly twice as strong as pearlitic ductile iron, ADI still retains high elongation and toughness. This combination provides a material with superior wear resistance and fatigue strength.

Chapter 3

Factors That Affect Properties of Ductile Iron

3.0 Introduction

Ductile iron is a special kind of material which exhibits a good combination of strength with ductility ensuring its huge application in heavy engineering industries. This is due to very typical microstructure owing to its chemical composition, heat treatment practice and processing variables. Some lists of important constituents which are responsible for its typical mechanical properties are discussed below.

3.1 Effect of Graphite Shape

As would be expected from the dramatic differences in mechanical properties between gray and ductile iron, that nodularity plays a significant role in determining properties within the ductile iron family. Nodularity, and the morphology of the non-spherical particles produced as nodularity decreases, exerts a strong influence on the yield and tensile strengths of ductile iron. When nodularity is decreased by reducing the amount of residual magnesium (the most common spheroidzing agent used in commercial ductile iron) the nodules become elongated, but do not become sharp or ‘spiky’. The result is a 10% decrease in yield strength and a 15% decrease in tensile strength when nodularity is reduced to 30%. Small addition of lead reduce nodularity by producing inter granular networks of spiky or plate-like graphite which result in dramatic reductions in tensile properties.

The effect of nodularity on pearlitic ductile irons can be determined by comparing the tensile properties, at constant carbide levels, of irons with nodularities 90, 70 and 40%. First, compared to the magnesium controlled loss of nodularity for the ferritic iron, the pearlitic iron is much more sensitive to reduce nodularity. Second, at low carbide levels typical of good quality ductile iron, there is relatively little loss of strength as the nodularity decreases to 70% but as nodularity deteriorates further, strength decreases more rapidly.

Designers can virtually eliminate the effect of nodularity on tensile properties by specifying that the nodularity should exceed 80-85% and that there should be no intercellular flake graphite. These criteria can be met easily by good production practices which ensure good nodularity through Mg control and prevent flake or spiky graphite by a combination of controlling flake-producing elements, their effects through the use of small additions of cerium.

3.2 Effect of Carbide in the Structure

Ductile iron castings are more prone to contain carbides than flake-graphite castings of similar section and size and carbon and silicon contents. This occurs partly because the spherodizing process generally involves the addition of magnesium and/or cerium, which are both elements to promote the formation of eutectic carbide; and partly because the sequence of solidification produced by the growth of nodular graphite tend to promote undercooling during solidification to temperatures at which white iron structure as likely to form. Carbides in ductile irons can occur in three forms:

Eutectic carbide (or chill) results mainly from the rapid solidification and is most prevalent in corners and thin sections. Inadequate inoculation, low carbon and in particular low silicon and the presence of carbide promoting elements increases the likelihood of carbides being present in the structure. Inverse chill, which has fine acicular form, occurs at or near the heat center of a casting section. The geometry of the casting and method of running the casting are important variables and the problem is often only solved by re-positioning or altering the size of ingates to change the pattern of solidification of casting.

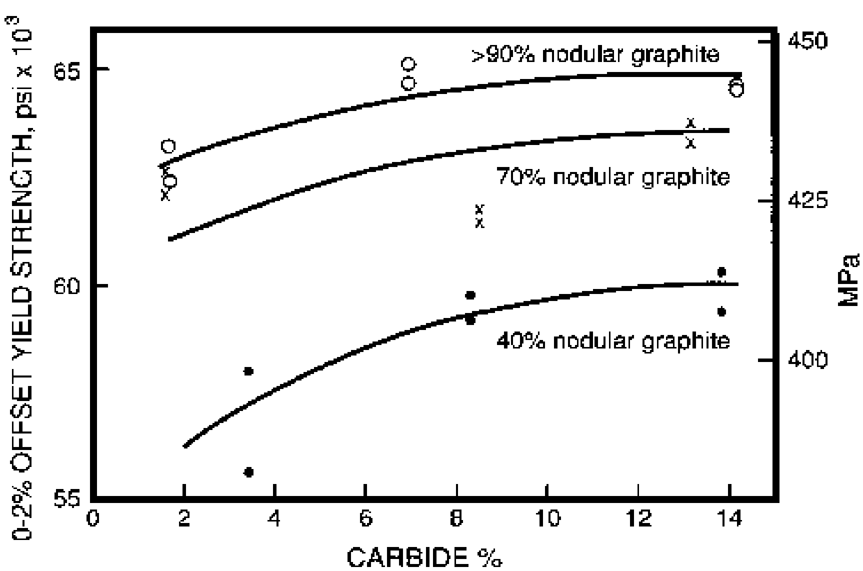


Fig.3.0.Effect of nodularity and carbide content on yield strength of pearlitic Ductile Iron.

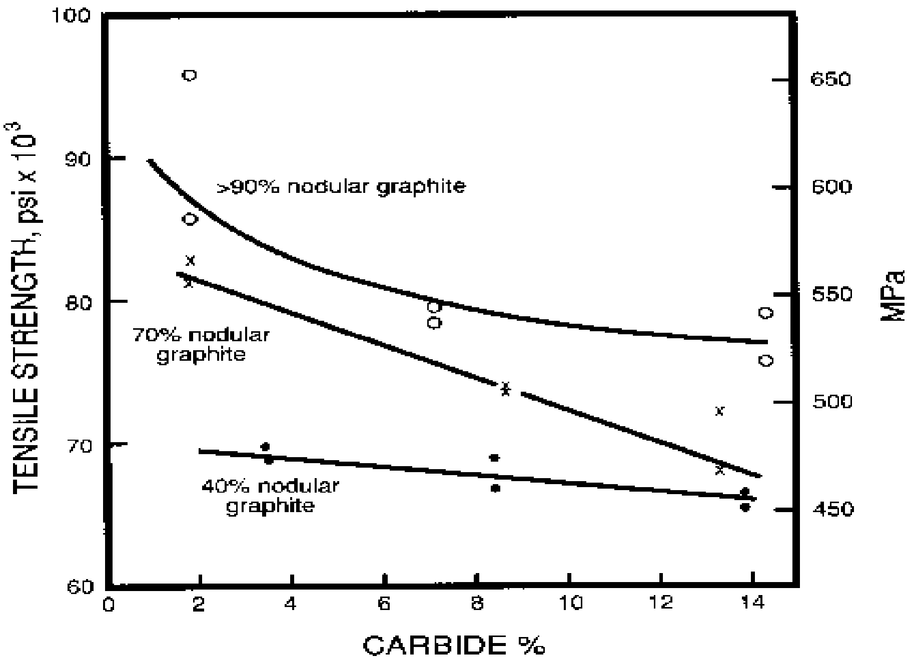


Fig.3.1.Effect of nodularity and carbide content on tensile strength of pearlitic Ductile Iron.

Segregation of carbides is more prevalent in heavy sections. They occur in the eutectic cell boundary area where the segregation of trace amounts of carbide-forming elements such as manganese or chromium occurs. These carbides do not readily respond to break down by heat treatment. The presence of carbide in ductile iron is undesirable for a number of reasons:

- It increases the tendency to form shrinkage porosity and thus increases the feeding requirements during casting.
- It increases the risk of cracking during knockout and fettling.
- It decreases the ductility of the iron.
- It drastically reduces the impact resistance.
- It increases hardness and reduces machinability.
- It requires heat treatment to 900-920^{o}C to remove the carbide.

The occurrence of all the three forms of carbide is minimized by efficient inoculation giving high nodule number and also by maintaining the contents of carbide promoting elements at low level. High silicon levels are also beneficial but the potential embrittling action of silicon contents much above about 2.6% should not be overlooked.

3.3 Effect of Nodule Count

Nodule Count, expressed as the number of graphite nodules/mm^2, also influences the mechanical properties of Ductile Iron, although not as strongly and directly as graphite shape. Generally, high nodule count indicates good metallurgical quality, but there is an optimum range of nodule count for each section size of castings, and nodule count in excess of this range may result in a degradation of properties. Nodule count has the following effects on microstructute, which can significantly influence properties,

- Nodule count influences the pearlitic content of as-cast ductile iron. Increasing the nodule count decreases the pearlite content, decreasing strength and increasing elongation.
- Nodule count affects carbide content. Increasing the nodule count improves tensile strength, ductility and machinability by reducing the volume fractions of chill carbides, and carbides associated with ‘inverse chill’.
- Matrix homogeneity is influenced by nodule count. Increasing the nodule count produces a finer and more homogeneous microstructure. This refinement of the matrix structure reduces the segregation of harmful elements which might produce intercellular carbides, pearlite or degenerate graphite.
- Nodule count affects graphite size and shape. Increasing nodule count results in a decrease in nodule size which improves tensile, fatigue and fracture properties. Inoculation practices used to improve nodule count often make the nodules more spherical. Thus, high nodule count is generally associated with improved nodularity.

3.4 Effect of Graphite Volume

The volume fraction of graphite in Ductile Iron can also influence certain tensile properties. Casting section size can influence both the volume fraction and size of graphite nodules. Increased section size reduces the cooling rate of the casting, causing more carbon to precipitate in the stable graphite phase, instead of the carbide phase favored by higher cooling rates. The lower cooling rates of the larger diameter bars also affect graphite nucleating potentials, resulting in reduced nodule count but increased nodule size. Graphite flotation can provide variations in graphite volume within larger castings which can be harmful to mechanical properties. Graphite flotation occurs when low cooling rates and high carbon equivalent combine to produce large nodules that rise during solidification. The result is a depletion of the larger nodules in the lower part of the castings and an accumulation at the upper surface. The increasingly pronounced curvature, with increasingly bar diameter is an indication of graphite flotation, in these larger bars, graphite flotation at higher carbon levels may have reduced the graphite volume in the centre of the bars from which the ¼ inch diameter test bar were machined.

The resultant reduced rate of increase of graphite volume with increased carbon would be reflected in flatter curves at higher carbon levels. Graphite flotation can cause a serious degradation of properties near the upper surface of large ductile iron castings. However, this phenomenon is readily avoided by reducing the carbon equivalent as the casting section size increases.

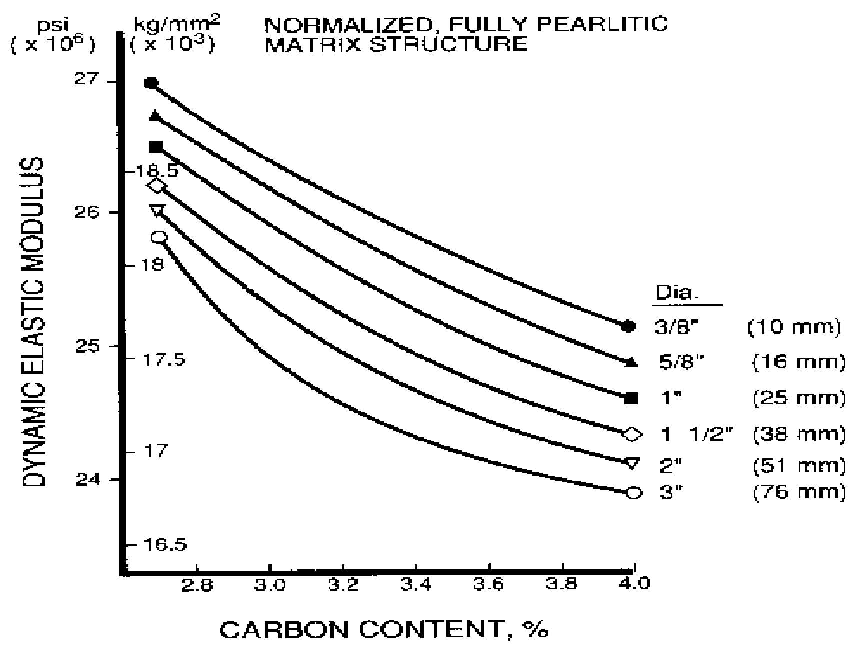


Fig.3.2 Effect of carbon content and casting diameter on the dynamic elastic modulus of fully pearlitic Ductile Iron.

3.5 Effect of Matrix

In Ductile Irons with consistent nodularity and nodule count and low porosity and carbide content, mechanical properties are determined primarily by the matrix constituents and their hardness. For the most common grades of Ductile Iron, the matrix consists of ferrite and/or pearlite. Ferrite is the purest iron phase in Ductile Iron. It has low strength and hardness, but high ductility and toughness and good machinability. Pearlite is an intimate mixture of lamellar cementite in a matrix of ferrite. Compared to ferrite, pearlite provides a combination of higher strength and hardness and lower ductility. The mechanical properties of ferrito-pearlitic ductile Irons are, therefore, determined by the ratio of ferrite to pearlite in the matrix. This ratio is controlled in the as-cast condition by controlling the composition of the iron, taking into account the cooling rate of the casting. It can also be controlled by an annealing heat treatment to produce a fully ferritic casting, or by normalizing to maximize the pearlite content. The exceptional as-cast properties of the fully ferritic base material – 455 Mpa UTS, 310 Mpa YS and 26% elongation for a Quality Index of 113: - are noteworthy. The Quality Indices of the samples, which were taken from different step bars, ranged from 90 to 113.

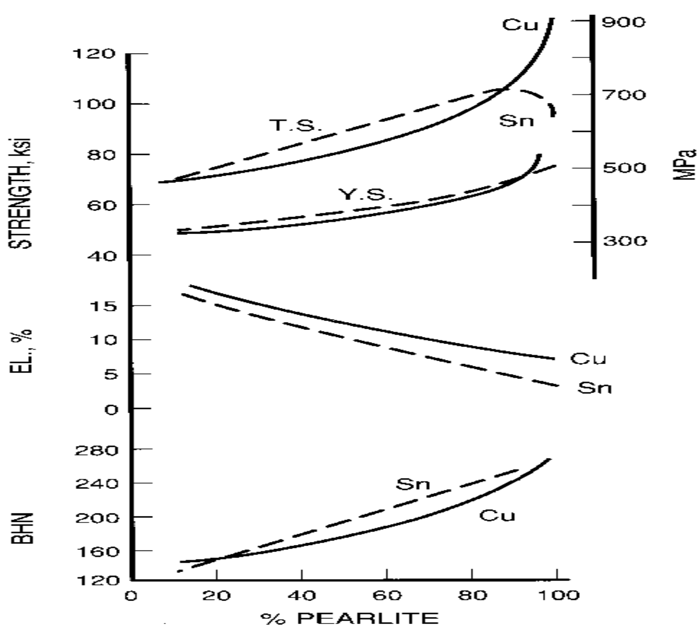


Fig 3.3.Relationship between tensile properties and pearlite contents of as-cast Ductile Iron.

3.6 Effect of Temperature on Design Stresses

When determining design stresses for a Ductile Iron component, the designer must be aware of both the temperature range in which the component will be operated and the effect of temperature on tensile properties. The increase in yield strength with decreasing temperature for both ferritic and pearlitic Ductile Irons suggests that higher design stresses may be used at low temperatures. Because most low temperature applications also involve performance at room temperatures, the room temperature yield strength must be used in the calculation of design stresses. However, the use of a yield strength-related design stress is acceptable for low temperature applications only when the applied stress state can be simulated by a quasi-static (low strain rate) test. In such cases, both ferritic and pearlitic grades may meet the design criteria. If the application involves impact loading, or if good notch toughness is specified, selection should be limited to ferritic grades. For special low temperature applications requiring maximum elongation and toughness, annealed ferritic grades should be used.

For temperatures up to 575^{o} F (300^{o} C), static design stresses can be based on the room temperature yield strength, as described earlier in this section. For temperatures above 650^{o}F (350 ^{o}C), design stresses should be related to creep data for applications in which dimensional accuracy is critical or stress rupture data when deformation can be tolerated but time-to-failure is critical.

3.7 Effect of Environment on Tensile Properties

Like some steels, the ambient temperature tensile properties of certain grades of Ductile Iron can be reduced significantly by prolonged exposure to certain environments. Figure 3.4 summarizes the effects of exposure for 30 days to air-saturated, distilled water on the tensile properties of Ductile Iron samples with different hardness levels. Yield strength was not affected by exposure until hardness exceeded 275 BHN, above which it decreased rapidly, attaining a loss of over 40% at a hardness of 430 BHN. Tensile strength and elongation followed similar trends, but the loss of strength and ductility began at lower hardness levels, 175 BHN, and increased more slowly, attaining the same level of reduction (40%) at 430 BHN. Figure 3.4 indicates that exposure to water for 30 days has no significant effect on the tensile properties of ferritic Ductile Irons, but those quenched and tempered to produce hardness levels above 250 BHN are embrittled to a degree which increases with hardness. Embrittlement may be due to a hydrogen-related phenomenon similar to that occurring in high strength steels.

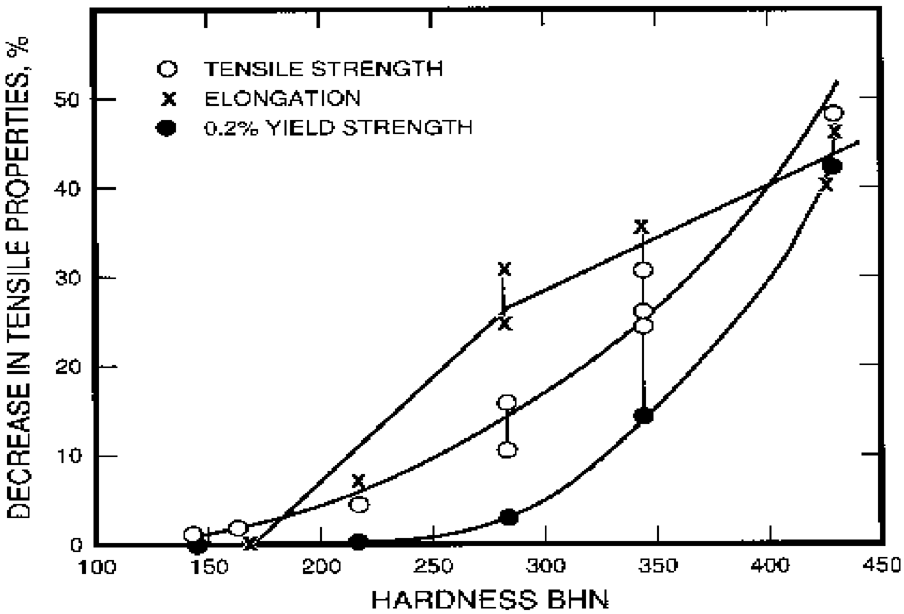


Fig.3.4 Degradation of tensile properties of Ductile Irons with different hardness levels after exposure to water for 30 days.

3.8 Effect of Metal Cleanliness

Under bending and torsional fatigue conditions in which the cyclic stresses reach a maximum at the component surface, fatigue strength is reduced by the presence of inclusions, dross, and other surface defects which act as crack initiation sites. Figure 3.5 shows that increasing the volume fraction of non-metallic inclusions significantly decreases fatigue strength. The influence of non-metallic inclusions on fatigue strength increases as matrix hardness increases. The increasing use of Ductile Iron components with as-cast surfaces places an increased importance on the elimination of surface defects for applications requiring optimum fatigue strength.

The reduction of dross-related surface defects through the use of filters in the mold filling system can result in a 25 per cent increase in fatigue life, as shown in The use of good foundry practices, including minimizing residual Mg content, careful deslagging of ladles, good gating and pouring practices, the use of filters in the gating system and the reduction of the effects of flake-forming elements in both the metal and molding materials, can result in fatigue strengths for as-cast surfaces.

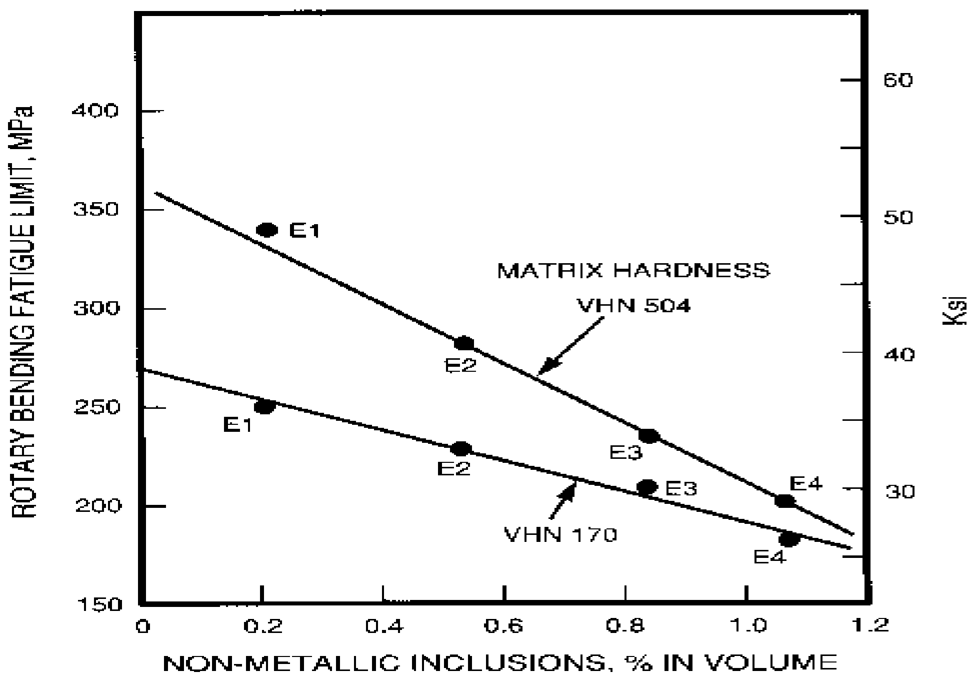


Fig.3.5 Effect of matrix micro-hardness and volume fraction of inclusions on fatigue limit of Ductile Iron.

3.9 Effect of Composition

In addition to the effects of elements in stabilizing pearlite or retarding transformation (which facilitates heat treatment to change matrix structure and properties), certain aspects of composition have an important influence on some properties. Silicon hardens and strengthens ferrite and raises its impact transition temperature; therefore, silicon content should be kept low as practical, even below 2.4%, to achieve maximum ductility and toughness.

Nickel also strengthens ferrite, but has much less effect than silicon in reducing ductility. When producing as-cast grades of iron requiring fairly ductility and strength such as ISO GRADE 500/7, it is necessary to keep silicon low to obtain high ductility, but it may also be necessary to add some nickel to strengthen the iron sufficiently to obtain the required tensile strength.

Almost all elements present in trace amounts combine to reduce ferrite formation, and high-purity charges must be used for irons to be produced in the ferritic as cast-condition. Similarly, all carbide forming elements and manganese must be kept low to achieve maximum ductility and low hardness. Silicon is added to avoid carbides and to promote ferrite as-cast in thin sections.

The electrical, magnetic, and thermal properties of ductile irons are influenced by the composition of the matrix. In general, as the amount of alloying elements increases and thermal conductivity deceases.

(A) Carbon (Graphite)

As the amount of graphite increases, there is relatively small decrease in strength and elongation, in modulus of elasticity, and in density. In GGG-50(ISO Grade) carbon requirement is 3.4-3.6%, for sufficient graphitization (nodules) to take place. *In the bath it should be 3.7-3.8% carbon to produce the product containing 3.5% carbon, as it is due to the loss taking place in solidification and in carbide formation.

In addition to influencing microstructural characteristics such as ferrite: pearlite ratio and carbide content, composition also affects the fracture behavior of annealed ferritic Ductile Iron. The influence of carbon content on notched impact properties is primarily on the upper shelf energy, which decreases with increasing carbon content, as shown in Figure 3.6. The influence of carbon in this region, in which fracture occurs by the formation of voids on graphite nodules, and the growth and coalescence of these voids, is to increase the number and size of nodules. Increasing carbon content thus reduces the plastic deformation required to grow and coalesce voids, resulting in reduced plastic fracture energy. This relationship between carbon content and limiting plastic fracture strain is consistent with the observation that elongation and other indicators of ductility in ferritic Ductile Iron increase with decreasing carbon content. (Fluidity, microstructural and shrinkage considerations normally require carbon levels above 3.2 per cent.)

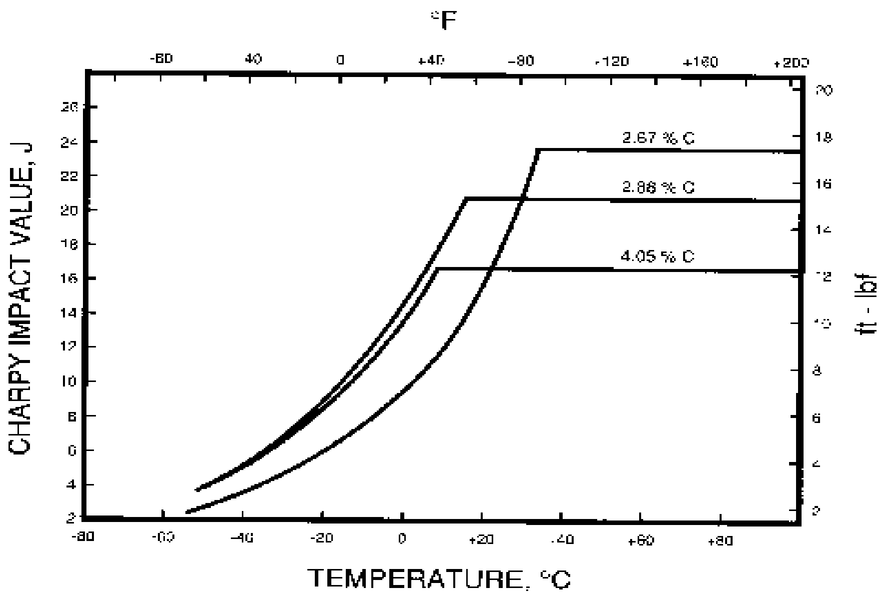


Fig.3.6 Effect of carbon content on the v-notched Charpy energy of ferritic Ductile Iron.

(B) Silicon

Silicon enhances the performance of ductile iron at elevated temperature by stabilizing the ferritic matrix and forming the silicon rich surface layer, which inhibits the oxidation. Stabilization of the ferrite phase reduces the high temperature growth in two ways. First, silicon raises the critical temperature at which ferrite transforms to austenite. The critical temperature is considered to be the upper limit of the useful temperature range for the ferritic ductile irons. Above this temperature the expansion and contraction of the surface oxide layer, reducing oxidation resistance. Then the strong ferritizing tendency of silicon stabilizes the matrix against the formation of carbides and pearlite, thus reducing the growth associated with the decomposition of these phases at high at high temperature.

So it is required in the acceptable range of “1.5-2.5”, because if the %age composition of Si will be more than 2.5, there will be appreciable decrease in the impact value. The oxidation protection offered by Silicon increases with increasing silicon content. Silicon levels above 4% are sufficient to prevent any significant weight gain after the formation of initial oxide layer.

The potentially objectionable influences of increasing silicon content are:→ **1)**. Reduced impact energy. **2)**. Increased impact transition temperature. **3)**. Decreased thermal conductivity.

Si is used to promote ferrite and to strengthen ferrite. So Si is generally held below 2.2% when producing the ferritic grades and between 2.5% and 2.8% when producing pearlitic grades.

The strong influence of silicon on the ductile-brittle transition temperature of ferritic Ductile Iron is shown in Figure 3.7. This Figure indicates that, to optimize low temperature toughness, silicon contents should be kept as low as possible. The successful production of as-cast carbide-free, low silicon Ductile Iron with a fully ferritic matrix requires high purity charge materials to minimize pearlite and carbide forming elements, controlled melting, holding and treating practices, and highly effective inoculation to maximize nodule count. The reduction in silicon level reduces both the yield and tensile strengths of the ferritic iron, and an offsetting addition of a less harmful ferrite strengthening element (such as nickel) is then needed to meet strength requirements. As with carbon, other considerations, especially microstructural control, require final silicon levels above 2%.

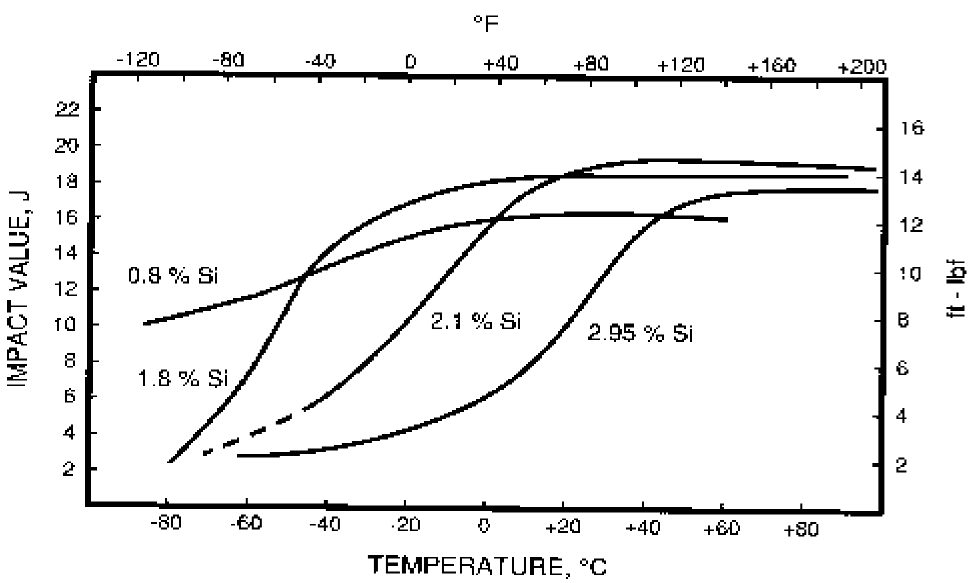


Fig.3.7 Influence of silicon content on the v-notched Charpy energy of ferritic Ductile Iron.

(C) Manganese

The decomposition of austenite to ferrite plus graphite or to pearlite in spheroidal graphite (SG) cast iron is known to depend on a number of factors among which are the nodule count, the cooling rate, and the alloying additions (Si, Mn, Cu, etc.).The detrimental effect of Mn on the growth kinetics of ferrite during the decomposition of austenite in the stable system is explained in terms of the driving force for diffusion of carbon through the ferrite ring around the graphite nodules. Finally, it is found that copper can have a pearlite promoter role only when combined with a low addition of manganese.

As it is a mild pearlite promoter, with some required properties like proof stress and hardness to a small extent, Mn retards the onset of the eutectoid transformation, decreases the rate of diffusion of C in ferrite and stabilizes cementite (Fe_3C), but the problem here is the embrittlement caused by it, so the limiting range would be 0.18-0.5%.

(D) Copper

The effect of various additions of copper and the cooling rate on the temperature of the onset of the stable and metastable eutectoid reactions describes the conditions for the growth of ferrite and of pearlite. These reactions can develop only when the temperature of the alloy is below the lower boundary of the ferrite/austenite/graphite or ferrite/austenite/cementite related three-phase field. Copper is a strong pearlite promoter. It increases the proof stress with also the tensile strength and hardness with no embrittlement in matrix. So in the pearlitic grade of the ductile iron the copper is kept between 0.4-0.8percent and is a contaminant in the ferritic grade.

(E) Nickel

It helps in increasing the U.T.S without affecting the impact values .So it can be used in the range of 0.4-2.0%. It strengthens ferrite, but has much less effect than Silicon in reducing ductility. As a Mild pearlite promoter, increases proof stress but little effect on tensile strength, but there is the danger of embrittlement with the large additions, in excess of 2%. Due to the high cost it is generally present as traces in the matrix. The irons treated with nickel have nodular graphite in a matrix of austenite with rather more carbide than the untreated irons.

(F) Molybdenum

It is a mild pearlite promoter. Forms intercellular carbides especially in heavy sections. Increases proof stress and hardness. Danger of embrittlement, giving low tensile strength and elongation value. And it also improves elevated temperature properties.

(G) Chromium

It prevents the corrosion by forming the layer of chromium oxide on the surface and stops the further exposition of the surface to the atmosphere. But as it is a strong carbide former so not required in carbide free structure and <1% required in the grade of GGG-50(ISO Grade) .it is kept around 0.05% Maximum. As a very strong carbide former, it should not be employed if carbide – free structure is required.

(H) Magnesium

Magnesium works as the modifier in the matrix and nodularises the graphite, increases the ductility and yield strength. Regardless of which process is used, the magnesium treatment must be effective, giving residual magnesium contents ideally in the range 0.04 – 0.05 percent, together with low final – sulphur contents (Less than 0.01 percent). Failure to obtain satisfactory levels of residual magnesium can be caused by one or several of the following:

- Excessive treatment temperature leading to high volatilization losses of magnesium.
- Inaccurate weighing of the treatment alloy, the liquid metal being treated of both.
- Loss of magnesium (Fading) – ladle treated metal should be poured within 10 minutes of the magnesium treatment alloy used.

Recent work at BCIRA has led to the development of a rapid foundry shop floor test based on thermal analysis [7].

In Mg treated irons, high Mg content acts to promote carbidic microstructures and increase shrinkage. The magnesium level must be controlled carefully to the cooling rate of the casting to avoid increased chilling tendency. This cooling rate is described as proportional to the modulus, which is a ratio of casting volume to cooling surface area. Thus modulus is a more accurate way to describe the cooling of a casting section than just measuring the section size. Obviously all of the carbide stabilizing elements should be kept to relatively low levels to minimize their effect on chill formation. This will then allow most of the available carbon to transform into graphite [8].

(I) Sulphur & Phosphorous

Phosphorous is kept intentionally very low, as it is not required because it causes cold shortness and so the property of ductile iron will be ruined. But the addition of S is done for better machinability, but it is kept around 0.009 and maximum up to 0.015%. As the larger additions of Sulphur may cause the hot (red) shortness.

(J) Tin

Tin is a strong pearlitic promoter,. There is a progressive increase in the amount of pearlite with increasing additions of tin. This is accompanied by a progressive increase in tensile strength, elongation and hardness. The microstructure is perfectly nodular with no flake graphite. The range of Tn% in the irons should be 0.05-0.1%. More than the above percentage, will increases proof stress and hardness but danger of embrittlement giving low tensile strength/ elongation values.

(K) Arsenic

Effect of arsenic is very similar to that of tin, but at least twice as much arsenic is required to achieve the same degree of pearlite stabilization as that of a given amount of tin. It is also clear that at least 0.09% arsenic can be tolerated without harmful effect on the formation of nodular graphite. Depending on the type of requirement of nodular iron, both arsenic and tin are to be considered subversive elements. If the aim is to produce a high strength iron with a pearlitic matrix, these elements may be ignored, but if the aim is to produce a relatively soft iron of good ductility, either in the as-cast condition or after heat treatment , then the amounts of tin and arsenic must be kept to a minimum.

(L) Antimony

Antimony is harmful to the mechanical properties of S.G Iron. It should not be used for the commercial production of S.G iron. It’s presence in the irons has a profound effect on the elongation values and the microstructures consisting of a small amount of flake graphite together with spherulitic nodules in a matrix containing considerably more amount of pearlitie.

(M) Lead

Lead shows harmful effect on the properties of nodular irons. If the liquid metal contains lead then cerium treatment is carried to neutralize the lead. It is observed that 0.009% lead began to have a subversive effect and 0.011% lead completely replaced nodular graphite with flake graphite.

(N) Bismuth

The amount of bismuth in the irons which can be tolerated depends upon the cooling rate of casting –larger amounts of bismuth can be tolerated in rapidly cooled sections than in slowly cooled sections. Bismuth in the amounts of the order of 0.003% begins to have a harmful effect, and 0.006% bismuth can completely inhibit the nodular structure.

(O) Aluminum

Aluminum inhibits the formation of spherulitic nodules and cause the formation of flake graphite structures in magnesium treated irons. It causes the retention o sulphur, which in turn causes the formation of flake graphite. Aluminum also has harmful effect even when the sulphur contents are normal for nodular irons.

(P) Titanium

Titanium probably occurs more frequently in foundry pig irons in amounts capable of easy detection than any other subversive element. The influence of titanium depends very considerably upon the magnesium content and the section size in which the metal is cast.

Chapter 4

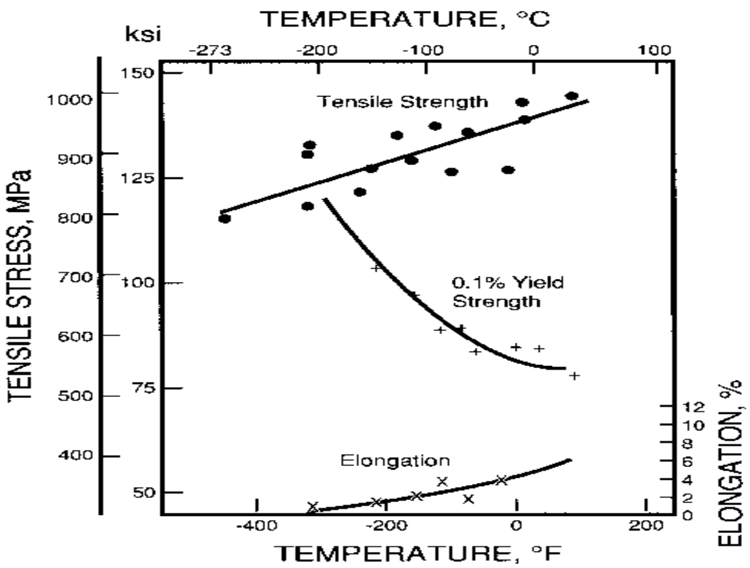
Mechanical properties of Ductile Iron

4.0 Introduction

The numerous, successful uses of ductile iron in critical components in all sectors of industry highlight its versatility and suggest many additional applications. In order to use ductile iron with confidence, the design engineer must have access to engineering data describing the following mechanical properties: elastic behavior, strength, ductility, hardness, fracture toughness and fatigue properties. Physical properties like thermal expansion, thermal conductivity, heat capacity, density, and magnetic and electrical properties are also of interest in many applications. This Section describes the mechanical and physical properties of conventional Ductile Irons, relates them to microstructure, and indicates how composition and other production parameters affect properties through their influence on microstructure.

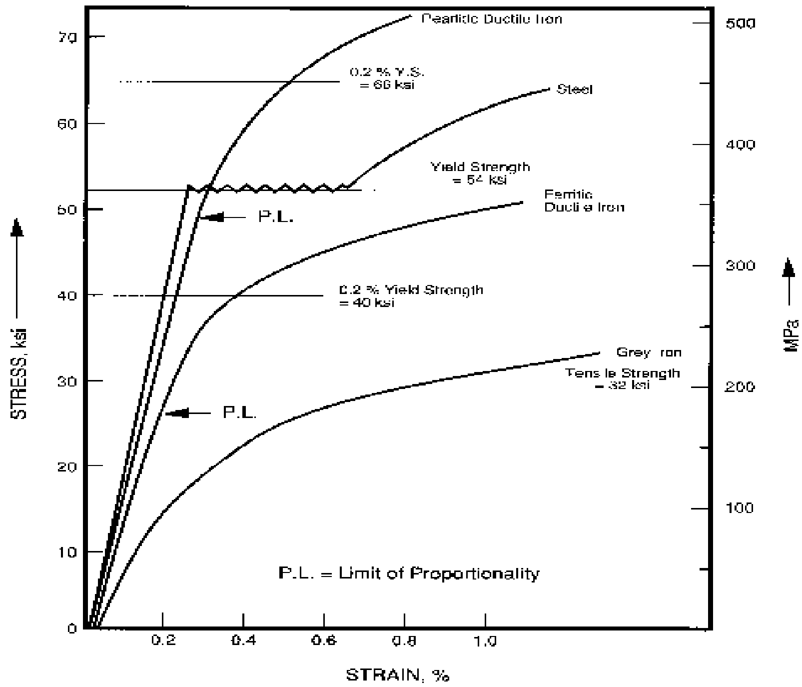
4.1 Tensile Properties

The tensile properties of conventional Ductile Iron, especially the yield and tensile strengths and elongation, have traditionally been the most widely quoted and applied determinants of mechanical behavior. Poisson's Ratio, the ratio of lateral elastic strain to longitudinal elastic strain produced during a tensile test, shows little variation in Ductile Iron. A commonly accepted value is 0.275. The proportional limit (also called the limit of proportionality) is the maximum stress at which a material exhibits elastic behavior. When a material is stressed below the limit of proportionality, and the stress is then removed, the stress-strain curve returns to the origin - no permanent change in dimension occurs. When the stress exceeds the proportional limit, plastic strain reduces the slope of the stress-strain curve. Upon removal of the stress, the strain decreases linearly, following a line parallel to the original elastic curve. At zero stress, the strain does not return to zero, exhibiting a permanent plastic strain, or change in dimension of the specimen (Fig.4.1). In Ductile Irons, which exhibit a gradual transition from elastic to plastic behavior, the proportional limit is defined as the stress required to produce a deviation from elastic behavior of 0.005%. It is measured by the offset method used to measure the yield strength and may also be estimated from the yield strength. The ratio of proportional limit to 0.2% yield strength is typically 0.71 for ferritic grades, decreasing to 0.56 for pearlitic and tempered martensitic grades.



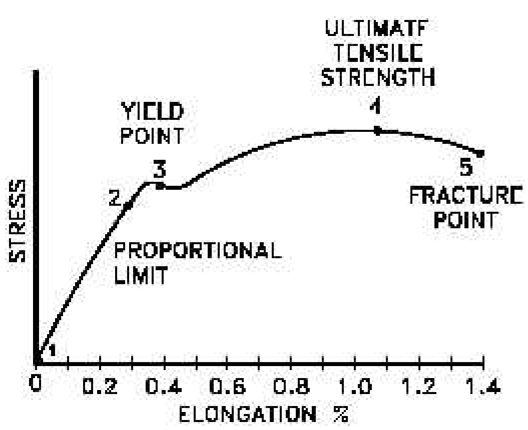
(Fig.4.1, Relationship between tensile properties)

The yield strength, or proof stress is the stress at which a material begins to exhibit significant plastic deformation. The sharp transition from elastic to plastic behavior exhibited by annealed and normalized steels (Fig. 4.2) gives a simple and unambiguous definition of yield strength. For Ductile Iron the offset method is used in which the yield strength is measured at a specified deviation from the linear relationship between stress and strain. This deviation, usually 0.2 %, is included in the definition of yield strength or proof stress in international specifications and is often incorporated in the yield strength terminology, e.g. "0.2 % yield strength". Yield strengths for Ductile Iron typically range from 40,000 psi (275 MPa) for ferritic grades to over 90,000 psi (620 MPa) for martensitic grades. The tensile strength, or ultimate tensile strength (UTS), is the maximum load in tension which a material will withstand prior to fracture. It is calculated by dividing the maximum load applied during the tensile test by the original cross sectional area of the sample. Tensile strengths for conventional Ductile Irons generally range from 60,000 psi (414 MPa) for ferritic grades to over 200,000 psi (1380 MPa) for martensitic grades.



(Fig.4.2.Elastic and yielding behavior for steel, Gray Iron and ferritic and pearlitic Ductile Irons.)

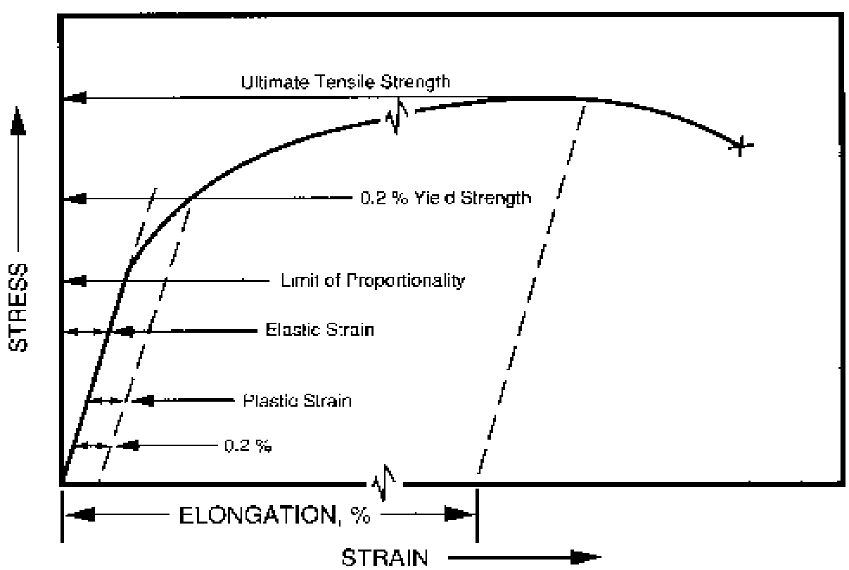
Although not specified, the modulus of elasticity and proportional limit are also vital design criteria. The modulus of elasticity for ductile irons, measured in tension, varies 162-170Gpa.Fig 4.3 shows typical stress-strain curve for ductile metals.



(Fig. 4.3, Typical stress-strain curve for ductile metals)

4.2 Elongation

Elongation is defined as the permanent increase in length, expressed as a percentage of a specified gage length marked in a tensile test bar, which is produced when the bar is tested to failure. Elongation is used widely as the primary indication of tensile ductility and is included in many Ductile Iron specifications. Although shown as the uniform elongation in figure 4.4, elongation also includes the localized deformation that occurs prior to fracture. However, because the localized deformation occurs in a very limited part of the gage length, its contribution to the total elongation of a correctly proportioned bar is very small. Brittle materials such as Gray Iron can fail in tension without any significant elongation, but ferritic Ductile Irons can exhibit elongation of over 25%.



(Figure 4.4, uniform elongation with localized deformation)

4.3 **Relationships between Tensile Properties**

The strong influence of graphite morphology and matrix structure on the different tensile properties of Ductile Iron produces significant correlations between these properties. Figure 4.5 illustrates the non-linear least square relationships between tensile and yield strengths and the dynamic elastic modulus. In 1970 Siefer and Orths, in a statistical study of the mechanical properties of a large number of Ductile Iron samples, identified a relationship between tensile strength and elongation of the form:

$$\textbf{(Tensile strength ksi)}^{2}\ \textbf{x (elongation \%)} \div \textbf{1000 = Q}$$

where Q is a constant.

A larger value of Q indicates a combination of higher strength and elongation and, therefore, higher material performance. Crews (1974) defined Q as the Quality Index (QI) for Ductile Iron. Both the QI and the underlying relationship between strength and elongation offer valuable insights into the quality of different Ductile Iron castings and the feasibility of obtaining various combinations of properties. High QI values have been shown to result from high modularity (high percentage of spherical or near-spherical graphite particles), absence of intercellular degenerate graphite, high nodule count, a low volume fraction of carbides, low phosphorus content (<O.03%) and freedom from internal porosity. High quality castings with these characteristics can be produced consistently by a competent, modern Ductile Iron foundry.

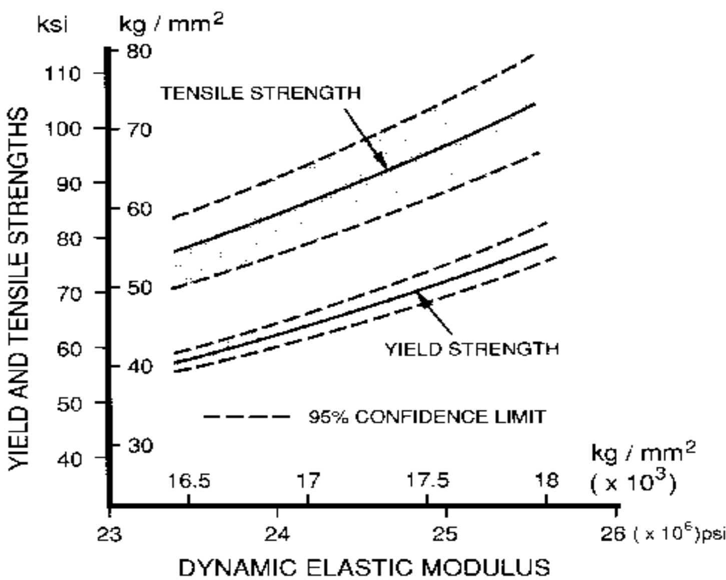


Figure 4.5 Relationships between yield and tensile strengths and dynamic elastic modules for Ductile Iron.

As might be expected from two decades of progress in ductile iron production technology and process control, the maximum quality index (QI) increased by 7.5%, but the median QI increased by 50%, indicating a significant improvement in consistency of properties.

4.4 Hardness

The hardness of Ductile Iron is usually and best measured by the Brinell test, in which a 10 mm diameter hardened steel or tungsten carbide ball is pressed into a flat surface of the work piece. Hardness is expressed as a Brinell Indentation Diameter (BID) or a Brinell Hardness Number (BHN). Hardness may also be described as BHN/3000 to indicate the force applied to the ball is 3000 kg, the normal value for ferrous materials. The sizes of the Brinell indentation, and its related volume of plastic deformation, are large relative to the scale of the microstructure and as a result an average hardness is obtained which exhibits good reproducibility for similar microstructures. Brinell hardness is included in many Ductile Iron specifications. Brinell hardness should be used for production control and as an auxiliary property test, for example to control machinability. Microhardness testing, using either the Knoop or Vickers indenters, can be used to measure the hardness of the individual components of the Ductile Iron matrix.

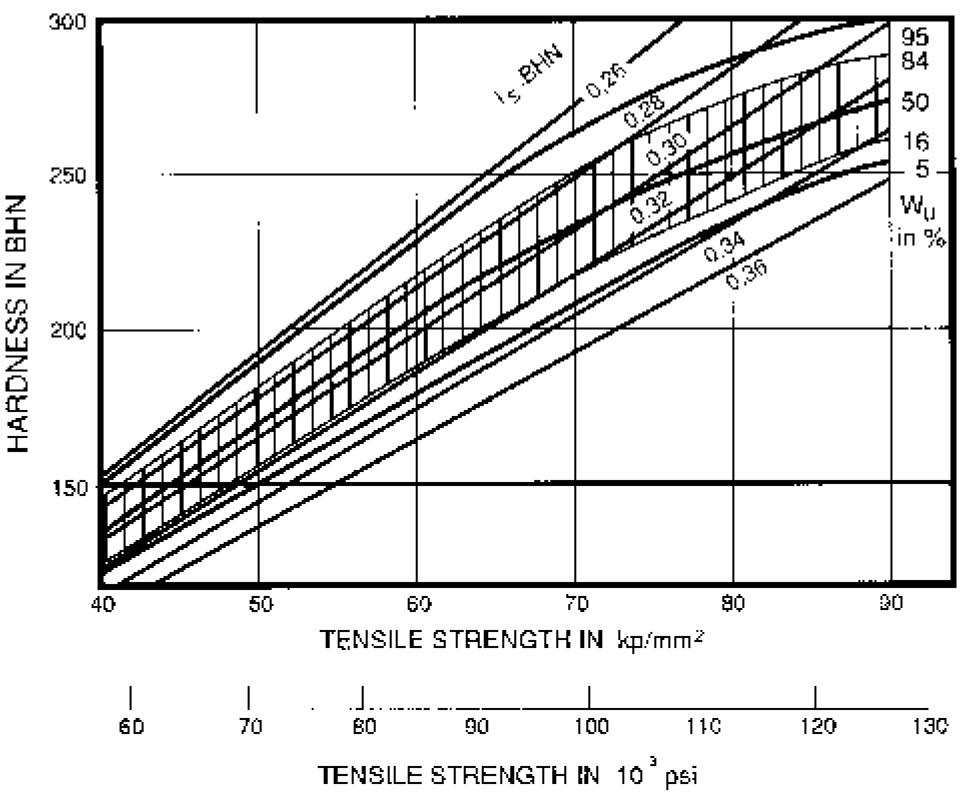


Figure 4.6, Relationship between Tensile strength and Hardness of ductile iron.

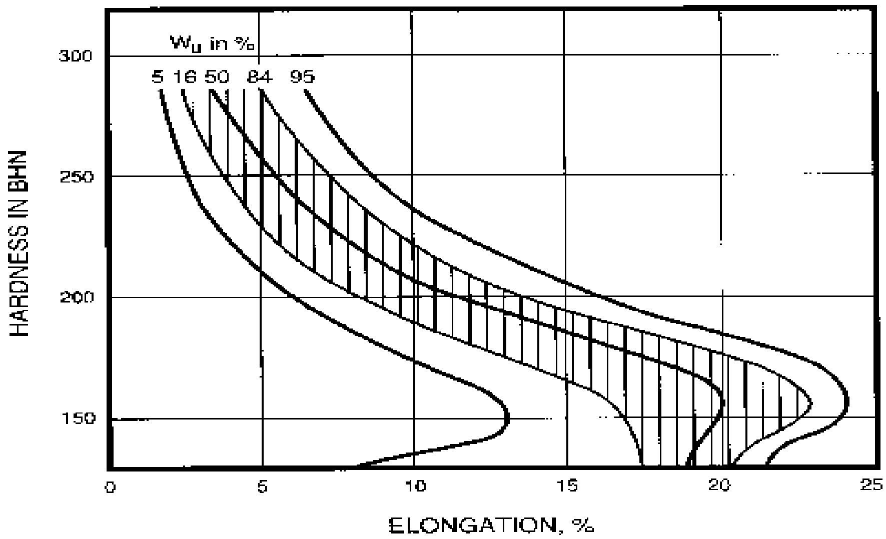


Figure 4.7, Relationship between elongation and hardness of Ductile Iron.

4.5 Machinability

To succeed in the fiercely competitive international markets for all finished products, from motor cycles to machine tools, manufactures must offer the end user the best value- the highest ratio of quality to cost. In order to maximize quality while minimizing the cost, designers have added manufacturability to the list of criteria that must be met by a successful design. This trend toward increasing importance of manufacturability has been confirmed by the results of a survey of 2500 design engineers conducted by the Ductile Iron Group. When asked to rank 19 materials selection criteria in order of importance, respondents placed both ease of machining and cost of manufacture in the top six.

The production of most finished metal products involves machining operations to produce the desired final shape. Castings offer the designer the lowest cost route for the production of complex shapes because they can be cast to near final shape, reducing both machining and materials cost. Near net shape casting technology and improved dimensional consistency offered by competent. Modern foundries, yield additional savings in manufacturing costs.

Ductile Iron, with its excellent castability, offers the designer all the manufacturing advantages of castings plus the added benefits of machinability: strength ratio that is superior to other cast irons and cast steels.

Machinability is not an intrinsic property of a material, but rather the result of complex interactions between the work piece and various cutting devices operated at different rates under different lubricating conditions. As a result, machinability is measured empirically, with results applicable only under similar conditions. Traditionally, machinability has been measured by determining the relationship between cutting speed and tool life because these factors directly influence machine tool productivity and machining costs.

4.6 Effect of Microstructure

Machinability is determined by microstructure and hardness. The graphite particles in ductile iron are responsible for the free-machining characteristics of this material and its superior machinability when compared to steels. Graphite particles influence cutting force and surface finish, the matrix is the primary determinant of tool life.

Hardness is often used as an indicator of machinability because of the close relationship between hardness and microstructure. However, hardness gives an accurate representation of machinability only for similar microstructures. For example, tempered martensite matrices will exhibit superior machinability to a pearlitic matrix of similar hardness.

Ferrite is the softest constituent in the matrix of ductile iron and as a result exhibits the best machinability. While not as soft as the ferrite in steels, the ferrite in ductile iron gives super machinability due to the effect of silicon, which decreases ferrite toughness, and the lubricating and chip-breaking effects of the graphite spheroids. Machinablility increases with silicon content up to about 3% but decreases significantly with increasing silicon content above this level.

Pearlite, which consists of an intimate mixture of soft ferrite and hard lamellar iron carbide, is a common matrix component in all intermediate strength grades of ductile iron. The volume fraction of pearlite and fineness of the lamellar determine the hardness and the machinability and wear resistance. Peralite fineness affects machinability and the effect of hardness decreases as pearlite fineness increases.

Carbides are the hardest constituents in the ductile iron and have the poorest machinability. When present as thin lamellar in pearlite they are easily sheared and are in their most machinable form. When present as massive or 'free' carbide, both iron and alloy carbides cause a dramatic reduction in machinability. Martensite is an extremely hard matrix phase produced by quenching ductile iron. It is too hard and brittle to be machined as quenched, but after tempering martensite is more machinable than pearlite of similar hardness.

Other structures such as acicular bainites and ferrite are produced by interrupted cooling in ductile irons with sufficient hardneability to suppress the formation of ferrite and pearlite. Acicular microstructures have a similar machnability to martensite tempered to the same hardness. Improved machinability is often one of the benefits gained when a steel component is replaced by Ductile Iron castings.

Chapter 5

Thin-Wall Ductile Iron, A Matter of Confidence

5.0 Introduction

Thin wall ductile iron (TWDI) castings constitute an attractive alternative to several applications in which the strength to weight ratio becomes a key design variable. In TWDI, the nodule count for a given chemical composition is highly dependent on cooling rate during solidification, and hence on thickness. For mechanical parts, where accurate dimensional tolerance is mandatory, the most common machining process applied is grinding. This process induces significant temperature gradients and surface plastic deformations which could affect service performance, particularly in corrosive environments.

Ductile iron is not a single material, but a family of materials offering a wide range of properties obtained through microstructure control. It has many advantageous characteristics which combine high strength, fatigue resistance, wear resistance, and higher performance at lower cost. If the yield stress/cost ratio of various materials is considered as-cast ductile iron is most of time the winner [9]. The manufacture of thin wall castings would not only prevent the transfer of ductile iron parts to light metals but would make possible the conversion of many steel assemblies to ductile iron [10, 11]. An attractive properties makes it convenient for instance in the automotive industry. Producing thin wall ductile iron castings is an important method for saving energy and materials. Take an automobile for example: a reduction of 100 kg in weight saves 0.5 liter of petrol per 100 km driven. Ductile iron is widely used for heavy construction equipment and safety relevant components in the fields related to nuclear energy also. Examples of safety relevant applications are turbine casing, rotating parts of transport systems like railway wheels or transport and storage casks for radioactive materials.

Chemically ductile iron is the same as grey iron and is iron-carbon-silicon alloy. The superior performance of ductile iron over grey iron has been attributed to the dis-similarity in graphite morphology of the graphite particles between the two materials. The common feature that all ductile irons share is the roughly spherical shape of the graphite nodules. These graphite nodules are nucleated on small inclusions during the solidification. The relative possibilities for nucleation and growth depend upon foreign particles or solutes present in the liquid, whether as trace impurities or as deliberate additions. When discussing the metallurgy of ductile iron, the main factors of influence on the structure that one needs to address are: chemical composition, cooling rate, liquid treatment and heat treatment. The main effects of chemical composition to nodular iron are similar to those described for grey iron, with quantitative differences in the extent of these effects and quantitative differences in the influence on graphite morphology. When changing the cooling rate, effects similar to those discussed for gray iron also occur in ductile iron, but the section sensitivity of ductile iron is lower. This is because spheroidal graphite is less affected by cooling rate than flake graphite. But pouring very thin sections in ductile iron presents danger of massive carbides as-cast [12].

5.1 Application of Thin-Wall Ductile Iron in Automotive Industry

The development of thin-wall technology allows the designers of energy consuming equipment to select the most appropriate material based on cost/material properties considerations, and not solely on density. The technology developed in this research project will permit the designers working for the automotive industry to make a better informed choice between competing materials and thin wall cast iron, thus decreasing the overall cost of the automobile. The following automotive ductile iron components were selected to illustrate the utilization of the mechanical and physical properties of various types of ductile iron.

(A) Rocker Arms

The production of ductile iron rocker arms was introduced by Ford in 1954 to capitalize on the ductility, heat treatability and manufacturing economics of ductile iron castings. Rocker arms are produced using a shell mold, stack molding method. This casting process produces thin wall castings with good dimensional accuracy and low molding cost. The castings are heat treated to breakdown any residual carbide to fully ferritize the matrix, thus providing maximum casting ductility. in the engine plant; the rocker arms are coined to final dimensions and surface finish. The only machining operation required is the drilling of one oil hole. Following these operations, the rocker arms are batch austenitized, oil quenched and tempered to provide the strength and wear resistance required for the final engine application.

(Figure 5.1, Rocker Arms)

(B) Rear axle Components.

Real axle carriers, gear cases, and gear case covers are typical examples of as-cast ferritic ductile iron casting application. Requirements for these types of components are good ductility, strength, and shock resistance as well as excellent machinability.

(C) Crankshafts

The automotive crankshaft is considered the “old reliable” ductile iron component. The first conversions from cast steel to ductile iron crankshafts began in 1951. The excellent field performance of the millions of ductile iron crankshafts used in automotive, truck, and tractor service atleast to the outstanding mechanical properties and quality of pearlitic ductile iron castings. While steel forgings are still used for special engine applications, with today’s ductile iron technology most of the remaining forged steel crankshafts could be successfully converted to ductile iron.

(Figure 5.2, Rear axle components)

(D) Ring and Pinion Gears

Prototype ring and pinion gear castings are shown in the following figure. Gearing represents major potential new applications which are for ductile iron. Ductile iron gearing can be cast as a toothed blank, significantly reducing the amount of material to be removed during machining. Compared with current forged steel practice, ductile iron offers the potential for major reduction in machining costs for components such as those shown.

(Figure 5.3, Prototype ductile iron ring and Pinion Gears)

(E) Follower Arms

The ductile iron follower arm used in the Ford 2 liter overhead cam engine built in Europe is included as an example of the response of ductile iron to specialized heat treatments to provide wear resistance for a severe service application. The follower arm sits on a stud near one end and contacts the valve to near the far end of its length. The camshaft rotates against a pad on the follower arm surface to control valve opening. The camshaft lobes are hardenable iron with a hardness of 50-60 Rockwell C. the follower arms require good machinability and excellent fatigue strength and wear resistance.

Chapter 6

A Brief Review of Previous Works

6.0 Introduction

Form the available literatures, it is quite evident that many attempts were made to understand and predict the behaviors of thin-wall ductile iron that includes the study of graphite morphology and its evolution, the response of matrix structure to heat treatment, structure and properties correlation, and its mechanical properties with different variables in as-cast condition and possible applications. A brief review of some literatures in these areas is presented hereunder.

6.1 A Review of Work Done by Earlier Researchers

The following subsections review some of the published research works addressing these issues.

R.C. Dommarco, M.E. Sousa, and J.A. Sikora [13] have investigated the Abrasion resistance of high nodule count ductile iron with different matrix microstructures. Thin wall ductile iron is being used in the industry as a way to improve the strength to weight ratio. Nevertheless, thin walled sections promote microstructural changes such as an important increase in the nodule count. The objectives of this process is to study the influence of the nodule count on the abrasion resistance of ductile iron castings, having different matrix microstructures, and analyze the main nodule characteristic affecting abrasion. Different ductile cast iron test samples, from 1.5 to 25mm in thickness, having nodule counts varying between 250 and 2000 nod/mm2, were used. The samples for abrasion tests were heat treated in order to adjust the matrices to fully martensitic, ferritic, pearlitic and ausferritic microstructures. The abrasion resistance was evaluated according to the ASTM G 65 standard. The results showed that in all cases, when the nodule count increases the abrasion resistance decreases, as a consequence of the increase in total amount of nodules perimeter exposed to abrasion which increase the overall rate of wear.

The results of the study show the negative influence of increasing nodule count on the abrasion resistance. The increase of wear rate with higher nodule counts is still evident for high resistance matrices. The negative influence of the increase of nodule count on the abrasive wear rate could probably be neglected for small variations in nodule count as those commonly found for ductile iron of regular thickness, but it becomes important as the nodule count increases. The use of Wl (length of the exit side of a nodule multiplied by the nodule count) allows estimating the abrasive wear concentration induced by the nodule count giving a good approximation to the shape of the curve E versus NC, when introduced in the equation representing the relative wear resistance (E). The *fab* factor proved to be an interesting tool to predict the relative abrasive wear rate of the matrices with different hardness and ductility response.

J.O. Choi , J.Y. Kim, C.O. Choi , J.K. Kim, P.K. Rohatgi[14] have investigated the effect of rare earth element on microstructure formation and mechanical properties of thin wall ductile iron castings. Ductile iron castings with 2, 3, 4, 6, 8, and 25mm thickness and various amount of rare earth elements (RE) (from 0 to 0.04%), were cast in sand molds to identify the effects of sample thickness and the content of RE% on microstructural formation and selected mechanical properties. The effects of RE content and sample thickness on microstructural formation, including on graphite nodule count, graphite nodule shape, spherodization, and ferrite amount, were observed. The yield strength of the samples with RE within the range investigated were lower than those of the specimens without RE. The elongation was improved with the addition of RE up to 0.03% in ductile iron castings. The additions of 0.02% RE caused a smaller graphite nodule size and a higher number of graphite nodules than those in the specimen without RE at all levels of RE addition; the nodule count decreased with increase in section size. The chill zones were observed in the 2mm thick samples, but were absent in the samples from castings which were thicker than 2 mm, irrespective of the addition of RE. The nodularity of graphite nodules improved due to the addition of 0.02–0.04% RE. The specimens with RE content up to 0.03% had a lower tensile strength and hardness, higher elongation than those of the specimens without RE. The ferrite content in all castings increased with additions of 0.02% RE. The tensile strengths of the 2 and 3mm thick samples were also estimated using the relationship between strength and hardness, obtained from the data on the tensile strength and hardness of the 25mm thick samples.

Microstructural features in thin wall ductile iron castings, including the thickness of ferrite layer around graphite ferrite, graphite nodule size, and graphite nodule count, were observed to depend on the amount of rare earth elements and sample thickness. In the 2mm thick specimens, the addition of RE leads to a decrease in the amount of chill formation, a higher graphite nodule count and size as compared to those in the specimens without RE. However, in the specimen whose thickness is in the range of 3–6 mm, the addition of RE led to a smaller graphite nodule size and a higher number of graphite nodules than those in the specimen without RE. These results suggest that the role of RE varies with sample thickness. In addition, chill formation was not observed in the samples thicker than 2 mm, irrespective of the addition of RE, suggesting that the effect of rare earth in reducing chill formation is important in very thin sections. The nodularity of graphite nodules improved due to the addition of RE. In the samples without RE, the nodularity increases with decreasing sample thickness; the RE addition significantly reduced the variation in nodularity with sample thickness. The amount of ferrite was observed to depend on RE content and sample thickness. The addition of RE led to a higher amount of ferrite than that of the specimens without RE. The ferrite content was the lowest for the 2mm thick specimen with 0.02% RE. The specimens with RE had a lower tensile and yield strength as compared to same thickness specimens without RE. The lower strength appears to be related to a lower amount of pearlite in the specimens with RE. The ductilities of the specimens with RE are lower than those of the specimens without RE.

C. F. Yeung, H. Zhao, and W. B. Lee [15] have investigated the Morphology of Solidification of Thin-Section Ductile Iron Castings. The morphology of solidified structures of thin-section ductile iron castings has been investigated by color metallographic techniques. Primary austenitic dendrites were found to be formed over the whole section of castings when the wall thickness was less than 14mm. The dendrites were thin and long, and the length and the number of dendrites depended on the solidification rate or the wall thickness of the casting. Growth of the dendritic arms was directional, being perpendicular to the surface of castings and along the wall thickness. Interdendrite segregation of Si and Mn is found to occur in thin-section ductile iron castings, as revealed by both color metallography and energy dispersive X-ray microanalysis. The segregation is more pronounced toward the center of castings.

It was found by color metallographic techniques that, with high undercooling, the primary austenitic dendrites that exist in thin-section ductile iron castings were formed at an early stage of solidification and were followed by the nucleation and growth of graphite spheroids. Unlike those of the dendrites in the normal ductile iron castings, the arrays of dendrites formed in thin-section ductile iron castings is directional, being perpendicular to the surface of castings and along the wall thickness. The length and the number of the dendrites depend on solidification rate or wall thickness. As the solidification rate decreases or the wall thickness increases, the dendrites decrease in number and length. It was observed by color metallography and verified by microanalysis that, in thin-section ductile iron castings, there exists an interdendritic segregation of Si and Mn, and Si tends to concentrate in the core of the primary dendrites, whereas Mn does so in the interdendritic area. The segregation is more pronounced toward the center of the castings.

R.C. Dommarco, A.J. Jaureguiberry, J.A. Sikora [16] have investigated the Rolling contact fatigue resistance of ductile iron with different nodule counts and matrix microstructures. Thin wall ductile iron castings are being used in the industry as a way to improve the strength to weight ratio of machine parts. The high cooling rate, suffered by thin wall parts during the solidification process, promotes several microstructural changes, such as, carbide precipitation and a noticeable nodule count increment. The study of this work shows the effect that the increase in nodule count has on the rolling contact fatigue resistance of ductile iron with different matrix microstructures. Ductile cast iron test samples, with nodule counts ranging between 150 and 1400 nod/mm2 were obtained. The samples were then heat treated in order to obtain three sets of different ADI grades and also a quenched and tempered set. The rolling contact fatigue properties were evaluated by using a flat washer type test rig. Different relations of the contact area versus the nodule size were obtained by using three different counterparts. The results show that an increase in the nodule count promotes a noticeable increase in the rolling contact fatigue life, being more important for the quenched and tempered samples. The relation between contact area surface and nodule size was the main variable influencing the rolling contact fatigue life.

The RCF testing procedure was modified in order to gain the possibility of testing with different contact areas by using different types of thrust bearings as a counterpart and, at the same time, maintaining constant the maximum contact pressure. Also, different nodule counts were obtained employing different solidification rates, allowing to study the influence of nodule size on the RCF resistance at different “contact area size versus nodule size (Cs/Ns)”. The results show that the nodule size affects the RCF life independently of the ductile iron microstructure, with a strong RCF life increment for the case of the quenched and tempered variant when the nodule size decreases. The RCF resistance is strongly affected by changes in the nodule size, but it can be also improved by the increase in the contact area, as it was demonstrated by testing with different contact areas sizes, while the nodule size was maintained constant.

A.D. Sosa, M.D. Echeverría, O.J. Moncada, S.N. Simison [17] have investigated the Surface reactivity of thin wall ferritic ductile iron, the effect of nodule count and grinding variables. Thin wall ductile iron (TWDI) castings constitute an attractive alternative to several applications in which the strength to weight ratio becomes a key design variable. In TWDI, the nodule count for a given chemical composition is highly dependent on cooling rate during solidification, and hence on thickness. For mechanical parts, where accurate dimensional tolerance is mandatory, the most common machining process applied is grinding. This process induces significant temperature gradients and surface plastic deformations which could affect service performance, particularly in corrosion environments. In TWDI, surface properties become more relevant due to the high surface area to volume ratio. Therefore, the aim of this work is to determine the effect of nodular count and grinding conditions on surface reactivity of ferritic TWDI. Electrochemical assays were carried out in a three electrode cell in a 3.5 wt. % NaCl solution on both polished and ground samples. The results obtained indicate that surface reactivity increases with higher nodular counts and residual plastic strain.

The surface reactivity of ferritic ductile iron is affected by nodule count and grinding variables. The increase in nodule count from 600 to 1500 Nod/mm2 promotes higher metal loss. Metal loss increases with strain hardening for all the experimental conditions tested.

D.A.Lo´pez, T.Perez, S.N.Simison [18] have investigated the importance of chemical composition and microstructure on CO2 corrosion of carbon and low alloy steels, their work has been widely recognized, but different aspects are still uncertain and contradictory results can be found in the literature. This is mainly due to the complexity of the problem and the difficulty to describe the involved mechanisms. The chemical composition and the microstructure are not independent variables; the same microstructure can be obtained with different chemical compositions and vice versa. Some authors report the effect of one of these parameters without taking into account that the other has been also modified. However, test conditions also vary widely, making them almost impossible to compare. As a consequence of the situation depicted above, it is evident that a more systematic work is required to clarify the mechanisms involved and to develop a selection criterion for the available information. The aim of this work is to review and discuss the available information about the effect of microstructure and composition of carbon and low-alloyed steel on corrosion resistance in CO_2 environments. The influence of these parameters on the efficiency of corrosion inhibitors is also considered.

From the analyzed data it can be seen that microstructure and chemical composition of carbon and low alloy steels are important factors and they have a significant influence on CO_2 corrosion performance. However, as remarked throughout this work, it is not possible to withdraw general behavior patterns, mainly due to the complexity of the issue and the interrelation within the different factors involved. However, some aspects can be highlighted and they could be useful for project and field engineers when selecting materials or corrosion control methods. In the case of carbon steels, the microstructure seems to have a major effect, although the information available at the present time is controversial and consequently the selection of materials is not an easy task. It is strongly recommended to be aware of it, and whenever possible, to perform online tests in order to monitor the corrosion rate and the inhibitors efficiency. If low chromium alloy steel is to be selected, it is worth noting that even when the influence of steel microstructure seems of less importance than for carbon steels, it is recommended not to have a ferrito-perlitic microstructure. When inhibitors are required, it is important to take into account that evaluation tests should be performed on the chosen steel since certain incompatibility among inhibitors and the chromium rich surface films grown on these steels have been reported. Then, as a general consideration, for any inhibitor selection, the chemical composition and the microstructure of the steel to be protected and to be taken into account. From the materials science point of view, it is clear that more systematic studies regarding the influence of the chemical composition and steel microstructure are still required in order to understand the nature of the surface films and their protectiveness, aiming to a better materials selection.

N. Rebasa, R. Dommarco, J. Sikora [19] has investigated the Wear resistance of high nodule count ductile iron. Thin wall ductile iron (DI) is being used in the industry as a way to improve the strength to weight ratios. The high cooling rate, suffered by thin walled parts as they solidify, promotes several micro-structural changes, such as, carbide precipitation, casting defects and a noticeable nodule count increment. The present work studies the effect that the increase in nodule count has on the resistance to abrasive and rolling contact fatigue (RCF) wear. Ductile cast iron test samples, with nodule counts varying between 100 and 1500 nod/mm2 were employed. The samples for abrasion tests were previously ferritized and then their wear resistance was evaluated according to the ASTM G 65 standard. The samples used in the RCF tests were first austempered and then evaluated by using a flat washer type test rig. The study shows that an increase in the nodule count promotes an increase in the abrasive wear rate. Otherwise, under the RCF wear mechanism, the high nodule count was highly beneficial, promoting a noticeable life increment of about six times.

The wear rate of DI was strongly affected by important variations in the nodule count, when the resistance to abrasion and RCF were evaluated. It was observed, in FDI samples, that the wear rate under abrasive conditions increases, due to the increase in nodule count. The analysis of the wear scars has shown that the nodules concentrate the damage in the form of a comet tail. Thus, higher the nodule counts the higher the abrasive wear rate. The RCF resistance of high nodule count ADI samples was more than five times higher than that obtained for normal nodule count ADI of similar hardness. From the different characterizing parameters of graphite distribution (size, count and nodularity), the nodule count seems to be mainly responsible for the longer lives observed in the high nodule count samples. The knowledge about the tribological response of thin walled DI parts will be important for design, in order to take into account the pros and cons of its application.

Yih-Hsun Shy, Cheng-Hsun Hsu, Shen-Chih Lee, Chih-Yuan Hou[20] have investigated the effects of titanium addition and section size on microstructure and mechanical properties of compacted graphite cast iron. Titanium is an anti-spheroidizing element and also carbide former in ductile iron. On the other hand, increasing the casting size essentially lowers the cooling rate that opposes the chilling tendency of titanium. This research was to study the combined effects of titanium and section size on their promotion of compacted graphite (CG) formation, and at the same time how matrix constituents were altered in heavy-wall castings. It was found that at the increasing casting thickness of 30 mm, 65 mm and 80mm, the percentage of CG increased while that of pearlite decreased either with or without titanium addition. However, titanium (added in an amount of 0.15 wt%) effectively promoted the formation of CG by over 10% and at the same time increased the pearlite content in the matrix. This was especially true in the thinner 30 mm casting. Irons with titanium addition exhibited a bit lower Brinell hardness, elongation, and impact toughness due probably to the higher CG percentage that facilitated easier crack propagation. However, comparing to the un-alloyed iron, fracture toughness increased along with tensile strength for iron with titanium addition in all casting sizes of 30–80mm. The higher pearlite content in the matrix has overridden the effect of increased CG percentage such that tensile strength and KIC value both increased.

In the range of compacted graphite percentage of 80–96% in this investigation, the effects of titanium addition and casting section size (mass) on microstructures and mechanical properties of heavy section 30–80 mm thick plates compacted graphite cast iron may be summarized as follows: Increasing section sizes promotes the formation of compacted graphite and ferrite due to slower solidification cooling rate. The increase in ferrite effectively decreased pearlite content in the matrix. This implied that the iron will generally turn weaker and softer with the increase of casting thickness. In each of the casting groups of CG iron with or without Ti addition, the above statement was found to be true in that hardness and tensile strength decreased while elongation increased a bit. However, both impact toughness and fracture toughness decreased, for different reasons, with increased section size despite the materials became softer and more ductile. Alloying with 0.15 wt% titanium effectively increased both the CG and pearlitic percentage, owing to the anti-spheroidizing and carbide-forming potentials of titanium. Increasing CG% weakened the material but increasing % pearlite strengthens it. These contradicting effects resulted in CG iron with titanium have their hardness and elongation stayed relatively unchanged while tensile strength only increased a bit. As to the effects of titanium addition on toughness behavior, it observed the same principles as the un-alloyed iron that higher %CG was the dominating factor in lowering the impact toughness of all the group B materials due to increased %CG from titanium addition.

A.D. Sosa, M.D. Echeverrıa, O.J. Moncadaa, J.A. Sikora [21] have investigated the Residual stresses, distortion and surface roughness produced by grinding thin wall ductile iron plates. This work deals with grinding effects on thin wall ductile iron plates. Residual stresses, shape distortion and surface roughness were measured on thin wall plates of different nodule count, ferritised and afterwards dry ground under several grinding conditions. In all cases, tensile residual stresses are maximum at the surface, and their profile decreases with depth until becoming compressive. No phase transformations can be observed at depths of up to 30 mm below surface, although plastic deformation is visible through nodules and grains enlargement. Distortion increases when the depth of cut and nodule count increase and the workspeed decreases. The mean stresses of the profile tensile zone also increase when the nodule count increases. Surface roughness improves slightly as nodule count increases and workspeed decreases. This tendency is more noticeable when depth of cut decreases. The arithmetic mean roughness (Ra) values obtained were always below 0.8 mm.

Grinding thin wall ferritised ductile iron plates led to plastic deformation, shape distortion and sign changes of the previously compressive residual stresses. For all nodule counts and grinding conditions, nodule and grain enlargement could be appreciated at depths of up to 30 mm below surface, as a consequence of the plastic deformation produced during grinding. The high residual dry grinding stresses turned out to be of tensile type, with maximum values at the surface and their profiles decreasing with depth until becoming compressive. Consequently, the plates experienced a curvature with concavity on the ground side, increasing with nodule count and depth of cut, and decreasing with workspeed. The mean stress of the residual stresses profile in the tensile area shows correlation with distortion, being greater for the highest nodule count samples. This behavior is attributed to its greater hardness and lesser plastic deformation. Roughness decreases with workspeed and increases with depth of cut, having this latter variable the greatest influence. Roughness decreases slightly as nodule count increases. This could be attributed to the greater microstructure refining. Ra values were always below 0.8 mm, representing a good quality surface for most industrial applications.

K.M. Pedersen, N. Tiedje [22] has investigated the Temperature measurement during solidification of thin wall ductile cast iron. Part 1: Theory and experiment. Temperature measurement using thermocouples (TCs) influences solidification of the casting, especially in thin wall castings. The problems regarding acquisition of detailed cooling curves from thin walled castings are discussed. Experiments were conducted where custom made TCs were used to acquire cooling curves in thin wall ductile iron castings. The experiments show how TCs of different designs interact with the melt and how TC design and surface quality affect the results of the data acquisition. It is discussed as to what precautions should be taken to ensure reliable acquisition of cooling curves. Measurement error depending on TC design and cooling conditions is shown. A method is presented that allows acquisition of cooling curves in thin walled ductile iron castings down to a thickness of at least 2.8 mm. The obtained cooling curves can be used to compare nucleation and growth during solidification of castings with different plate thicknesses.

Using unsheathed thin thermocouple wire, e.g. a diameter of 0.2 mm, mounted in a thin ceramic tube, e.g. a diameter of 1.6 mm, so that the thermocouple wire is immersed naked in the melt, it is possible to obtain reliable cooling curves in the thin walled casting. The obtained cooling curves can be useful when comparing nucleation and growth during solidification of different castings, including different plate thicknesses. The two thermocouple wires do not need to be welded if there is electrical contact between melt and the wires. If there is electrical contact between melt and thermocouple wire, making a short circuit, the measuring point can best be defined as the point where the short circuit starts. The microstructure of the casting around the thermocouple was not affected by the presence of the thermocouple. During filling of the mould with ductile iron the thermocouple wire was surrounded by an oxide layer from surface of the melt. This layer was initially giving a heat transfer coefficient (HTC) between thermocouple wire and melt of about 25,000 Wm^{-2} K^{-1} estimated from the heating time between measured temperatures of 200– 1000 ^{o}C. Later, the oxide layer decreased in thickness or it disappeared and the thermocouple wire was partly dissolved by the melt, which is assumed to give a very high HTC between thermocouple wires and melt. To achieve good measurements it is important that the melt is allowed to flow past the thermocouple for as long time as possible so that the thermocouple is cleaned by the melt and is at thermal equilibrium with the surroundings.

Chapter 7

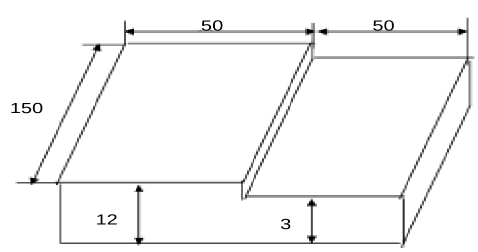
Experimental Procedures

7.0 Introduction

This chapter introduces the experimental procedures utilized to characterize the thin-wall ductile iron studied.

7.1 Melting and Casting

Fifteen melts of nodular iron were produced using open ladle treatment method for this study. Charges consisting 50kg pig iron (C=4.17%, Si=1.66%, Mn=0.138%, S=0.024%, P=0.060%), 100kg S.G return (C=3.62%, Si=2.12%, Mn=.19%, S=0.010%, P=0.026%) and 150kg steel scrap (C=0.038%, Si=0.037%, Mn=0.135%, S=0.005%, P=0.015%) were melted in 250kg capacity coreless medium frequency induction furnace. The molten metal was tapped in a preheated laddle containing Ferro silicon magnesium alloy of size 15-25mm (Si=45.50%, Mg=5.85%, Ca=1.08%, Al=0.91%) at the bottom covered with steel scrap. The tapping temperature of molten metal was 1450^{o}C.Commercial argon gas was punched through steel pipe to the melt for proper mixing with addition of 1% Ferro silicon inoculants (3.5kg) of size 2-6mm (Si=73.52%, Al=1.06%, P=0.035%, S=0.004%, Ca=0.19%, Ba=2.00%). At this time the sample was taken from the melt for final chemical analysis. The treated iron was poured into furan resin sand molds (Step bar specimen of size as sown in figure 7.1) bonded with epoxy resin and catalyst. The pouring temperature was 1380^{o}C. Similarly other fourteen melts were prepared with varying chemical composition and all melts were properly post inoculated. The chemical compositions of all the raw materials used are obtained from manufacturer's analysis.



(Fig. 7.1 Schematic drawing of step bars, 3 and 12 mm sections, Dimensions are in mm)

7.2 Test Specimen Preparation

Tensile testing specimens were made from casting obtained from step bars and their tensile strength; yield strength and elongation were measured using Universal Testing Machine (model- UTE 100, max.capacity-1000 KN, Make-Fuel Instruments & engineer's pvt.ltd, Maharahstra, India) as per ASTM standard. Charpy impact test at -20^{o}C in a Shimadru pendulum of 50J maximum capacity was performed with notched specimen(10x10x55mm and subsize 2.5x10x55mm,BSEN 10045-2-1993) cooled in a bath for 5 minutes containing methanol and dry ice for temperature down to -20^{o}C.The impact values were calculated taking average results of three specimens. The schematic diagrams of the specimens are shown in figure 7.2(A, B&C)

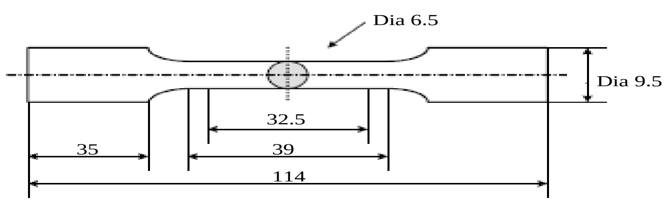


Fig 7.2A, Round Tensile Test Specimens (dimensions are in mm)

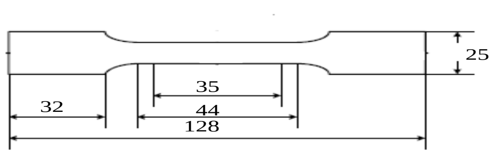


Fig 7.2B, Flat Tensile Test Specimens (dimensions are in mm)

Hardness tests were also performed on each sample using Brinell Hardness Tester. Average values of the hardness were obtained based on 5 measurements. A 3000kg load was applied to specimens with thickness 12mm and 500kg for 3mm sections.

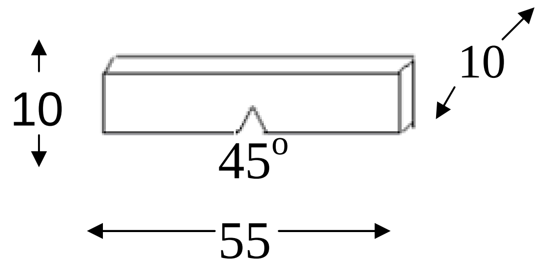


Fig 7.2C, V-Notched specimen for charpy impact Test (dimensions are in mm)

Salient Features of Universal Testing Machine:

- Rupture (% peak) = 50
- Preload (% full scale) = 0.05
- Safe Load (KN) = 900
- Hold Time (sec.) = 10
- Load Rate (KN/min) = 65
- Stress Rate (KN/sq.mm/min) = 10
- Elongation Rate (mm/min) = 2
- Strain Rate (% strain/min) = 1
- Initial valve open (10-99%) = 25

7.3 Optical Microscopy

The samples for microstructural observation were taken from the centre of the thin-wall casting and mounted with Bakelite. The surfaces of the samples were ground on SiC paper from 220 to 800 grit and polished with 1µm cloth coated with diamond paste. The samples were etched with 2% nital (2% conc. Nitric acid and 98 ml Methanol solution). Then optical micrographs were taken with a 35 mm camera attached to a Leitz microscope.

7.4 Analysis with Image Analyzer

The mounted samples after metallographic analysis were put under Image Analyzer (Make-Correct Tokyo, Seiwa optical) to investigate the nodule counts, nodularity and percentage of ferrite and pearlite content in the samples.

7.5 Spectrometric Analysis

The final chemistry for each melt was determined using Spectrometer (Spectro lab, M-9 model, Jerman make). The features of the spectrometer (M9-model) are extraordinary from other models. It takes 30 seconds for analyzing the composition of each sample and gives accurate percentage of 23 elements present in the sample.

7.6 Preparation of Furan Resin Sand

The Furan resin sand was prepared by self setting furan binder system, in a mixture (Make- Impianti Macchine Fonderia, Italy) taking 1.2% epoxy resin, 45% catalyst, 60% reclaimed sand and 40% fresh silica sand. The foundry grade resin used was urea formaldehyde/furfural alcohol and the catalyst used was para-toulene sulphuric acid. They harden by polymerization at room temperature under the influence of acid catalyst. The sieve analysis of fresh silica sand, reclaimed sand and physical testing of furan resin sand (as per ISS 460 standard) was carried out using sand testing equipments. The sand specimen prepared for physical testing is shown in fig 7.3 and the testing result was given in table-1,150gm of furan resin sand was taken for preparing each specimen.

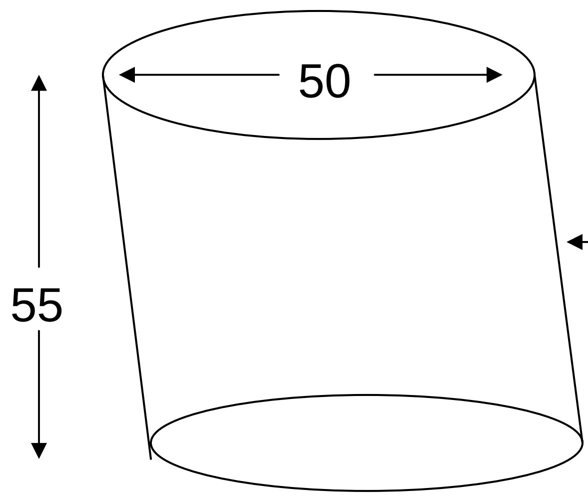


Figure 7.3, furan resin sand specimen (Dimensions are in mm)

The testing result of furan resin sand is given below.

Dry permeability	>500 (mm head of water)
Dry compressive	32.0 (Testing time: after 4 hours of sample preparation)
Strength (kg/cm^2)	40.0 (Testing time: after 8 hours of sample preparation)
	48.0 (Testing time: after 24 hours of sample preparation)

Table: 1 (Result of Furan Resin Sand Specimen)

Type of sand	Moisture (%)	Clay (%)	AFS(GFN) (%)	GD (%)	Density (gm/cc)	LOI (%)	ADV (%)	Sulphur (%)
Fresh	0.05	0.18	41.26	81.8	1.42	0.30	0.47	0.038
Reclaimed	0.10	0.39	43.56	85.40	1.47	4.80	2.52	0.061

GFN- Grain fineness number, GD-grain distribution, LOI-loss of ignition, ADV- acid demand value.

The final chemistry of five melts (M-1 to M-5) which were analyzed in spectrometer is given in table- 2.

Table: 2 (Final Chemistry of M-1 to M-5)

Melt No.	C%	Si%	Mn%	S%	P%	Cr%	Ni%	Mo%	Cu%	Mg%	CE%
M-1	3.50	2.05	0.18	0.010	0.021	0.024	0.020	0.002	0.03	0.050	4.18
M-2	3.55	2.15	0.19	0.009	0.023	0.028	0.021	0.001	0.026	0.045	4.26
M-3	3.60	2.25	0.18	0.011	0.025	0.022	0.022	0.002	0.028	0.040	4.35
M-4	3.65	2.35	0.20	0.009	0.027	0.023	0.020	0.001	0.03	0.035	4.43
M-5	3.70	2.45	0.21	0.012	0.029	0.022	0.021	0.001	0.029	0.030	4.52

Chapter 8

Results & Discussion

8.0 Effect of Chemical composition on Tensile Properties.

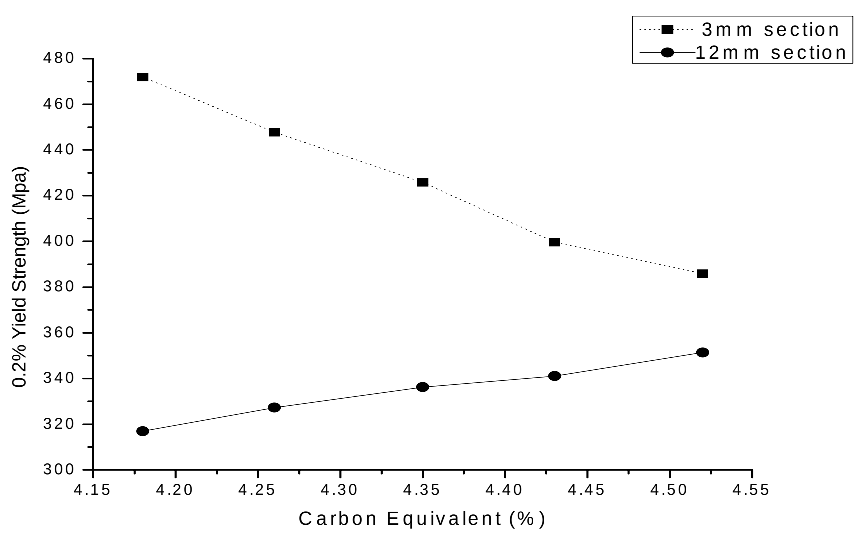
(A) Effect of Carbon Equivalent (CE):

The effect of carbon equivalent (CE) on the yield strength and tensile strength in 3 and 12 mm sections is given in Fig. 8a and 8b and the data given in table-3.

Table: 3 (Tensile properties of M-1 to M-5)

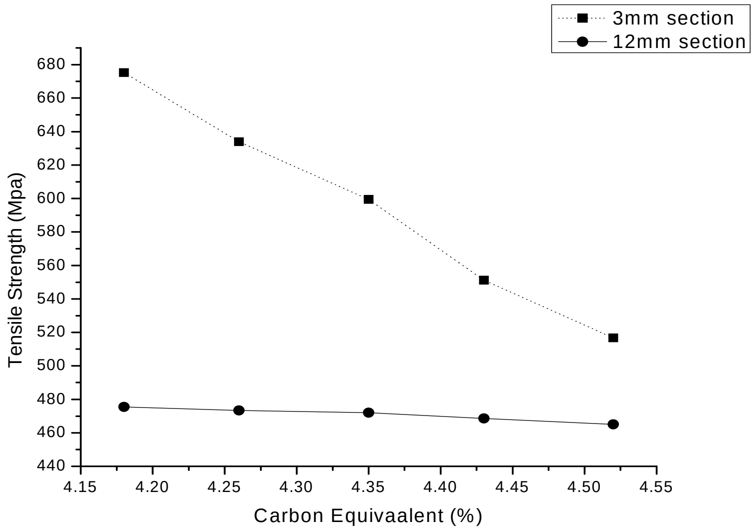
Melt. No	C.E (%)	0.2% Y.S(Mpa) (3mm sec.)	0.2% Y.S(Mpa) (12mm sec.)	T.S.(Mpa) (3mm sec.)	T.S.(Mpa) (12mm sec.)
M-1	4.18	471.95	316.94	675.22	475.41
M-2	4.26	447.85	327.28	633.88	473.34
M-3	4.35	425.80	336.23	599.43	471.96
M-4	4.43	399.62	341.05	551.20	468.53
M-5	4.52	385.84	351.40	516.75	465.08

Y.S: Yield strength, T.S: Tensile strength, Sec.: section



[Fig 8a, Effect of Carbon equivalent on 0.2% Yield Strength]

The result shows both the yield and tensile strength of 3 mm sections decrease significantly with an increase in CE, as a result of increase in ferrite content. On the other hand, 12 mm sections show a slight increase in yield strength with an increase in CE but the tensile strength does not show any effect.



[Fig 8b, Effect of Carbon equivalent on Tensile Strength]

Fig. 9a and 9b show changes in elongation with CE and carbon on 3 and 12 mm sections. The increase in CE shows a small improvement in the elongation of 12 mm sections as a result of increase in ferrite but the 3mm sections are not much affected by changes in CE. The elongation of 3 mm sections slightly reduces with an increase in carbon content but the 12 mm sections show improvement in elongation. The increase in carbon content results in a slight increase in the strength of 3 mm sections, whereas the strength of 12 mm sections do not significantly vary despite changes in the carbon content as shown in Fig. 10a and 10b. The data given in table-4.

Table: 4 (Physical properties of M-1 to M-5)

Melt. No	CE%	C%	0.2% Y.S(Mpa) (3mm section.)	0.2% Y.S(Mpa) (12mm section.)	T.S(Mpa) (3mm section.)	T.S(Mpa) (12mm section.)	EL% (3mm section.)	EL% (12mm section.)
M-1	4.18	3.50	471.95	316.94	675.22	475.41	5.10	15.0
M-2	4.26	3.55	447.85	327.28	633.88	473.34	5.20	16.0
M-3	4.35	3.60	425.80	336.23	599.43	471.96	5.20	17.0
M-4	4.43	3.65	399.62	341.05	551.20	468.53	5.22	17.5
M-5	4.52	3.70	385.84	351.40	516.75	465.08	5.30	18.0

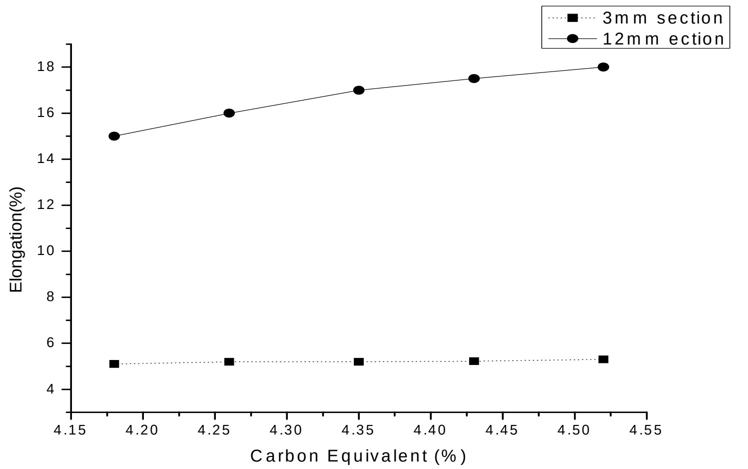


Fig. 9a, Effect of CE on elongation of 3 & 12mm sections

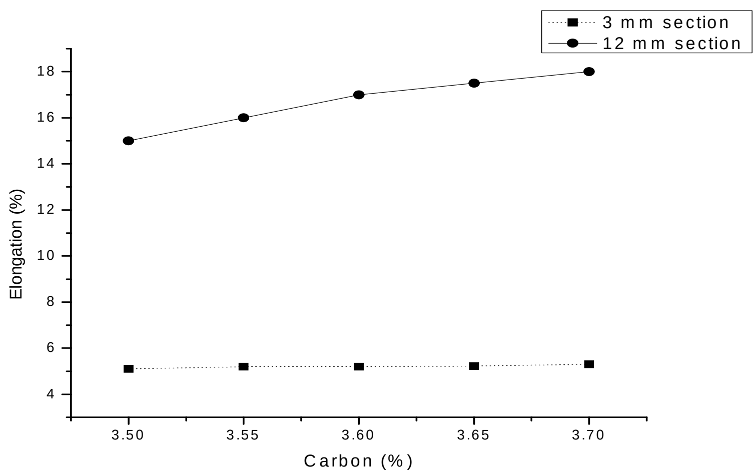


Fig. 9b, Effect of carbon on elongation of 3 & 12mm sections

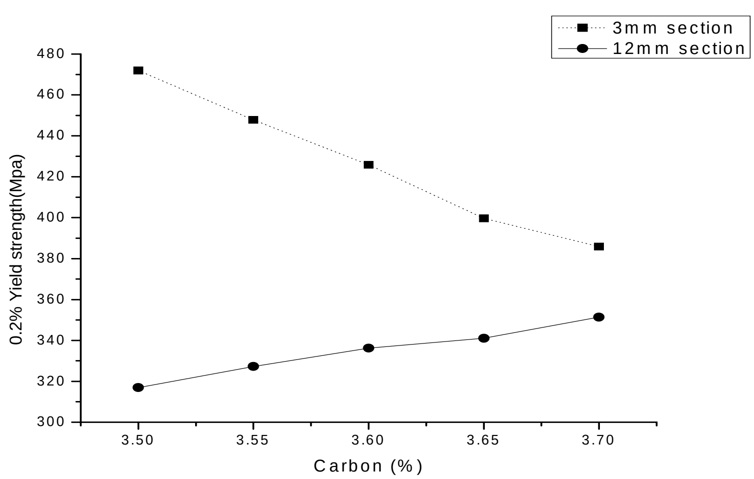


Fig. 10a, Effect of carbon on yield strength of 3 & 12mm sections

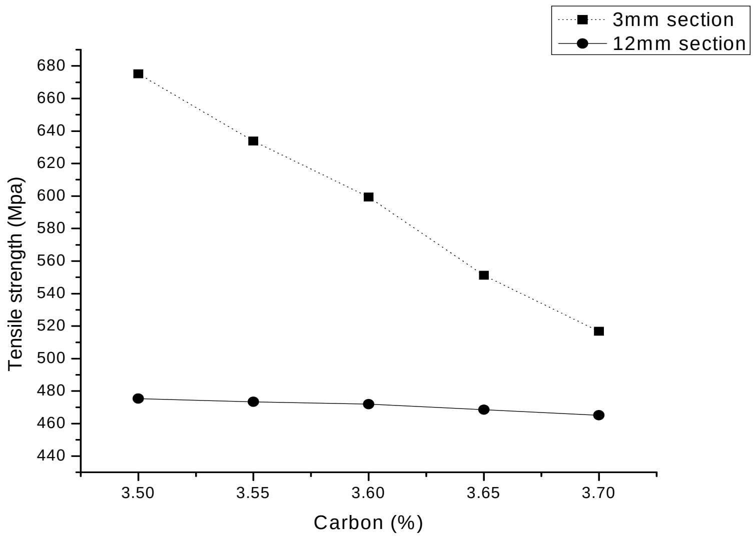


Fig. 10b, Effect of carbon on Tensile Strength of 3 &12mm sections

(B) Effect of Silicon:

Silicon shows the most significant effect on the tensile and yield strength of 3mm sections, as shown in Fig. 11a and 11b. This decrease in strength results from the increase in ferrite content/nodule count with an increase in silicon content. The 12 mm sections show a moderate increase in yield strength with an increase in silicon content due to the solid-solution strengthening of the ferrite, whereas the tensile strength is not much affected by change in the silicon level. A strong effect of silicon in increasing the elongation of both 3 and 12 mm sections is shown in Fig. 12a. The data given in table -5.

Table: 5 (Physico-chemical properties of M-1 to M-5)

M.No.	Si%	Mg%	Ce%	0.2%YS (Mpa) (3mm section)	0.2% YS(Mpa) (12mm section)	T.S.(Mpa) (3mm section)	T.S(Mpa) (12mm section)	EL (%) (3mm section)	EL (%) (12mm section)
M-1	2.05	0.050	0.004	471.95	316.94	675.22	475.41	5.10	15.0
M-2	2.15	0.045	0.006	447.85	327.28	633.88	473.34	6.00	16.0
M-3	2.25	0.040	0.008	425.80	336.23	599.43	471.96	7.20	17.0
M-4	2.35	0.035	0.010	399.62	341.05	551.20	468.53	7.80	17.5
M-5	2.45	0.030	0.012	385.84	351.40	516.75	465.08	8.50	18.0

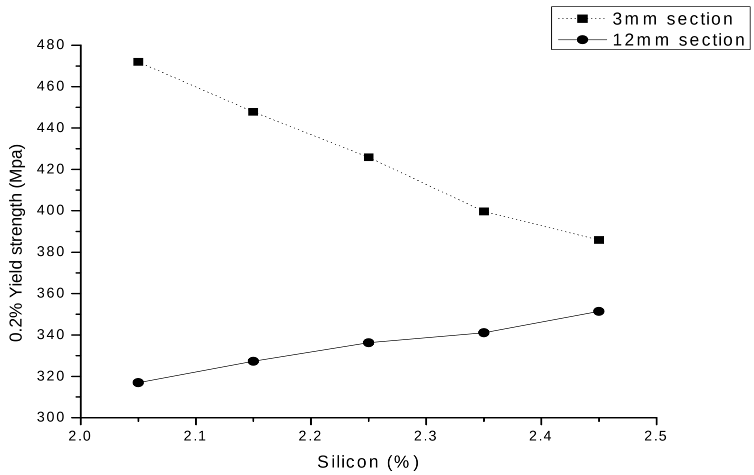


Fig. 11a, Effect of silicon on yield Strength of 3 & 12mm sections

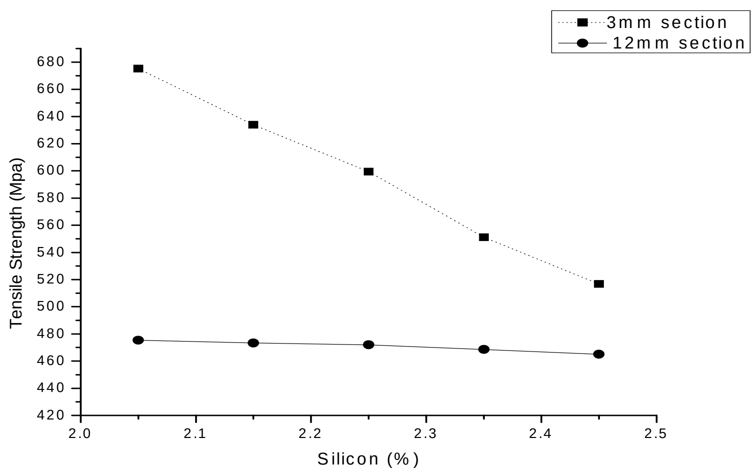


Fig.11b, Effect of silicon on Tensile Strength of 3 & 12mm sections

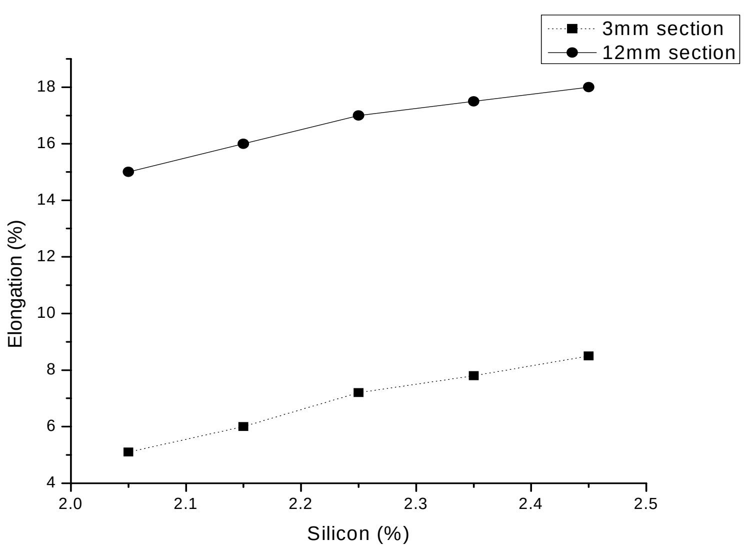


Fig. 12a, Effect of silicon on elongation of 3 & 12mm sections

(C) Effect of Magnesium:

An increase in Mg content is shown to decrease the elongation in both 3 and 12 mm sections (Fig. 12b) as a result of carbide stabilizing effect of Mg in cast iron.

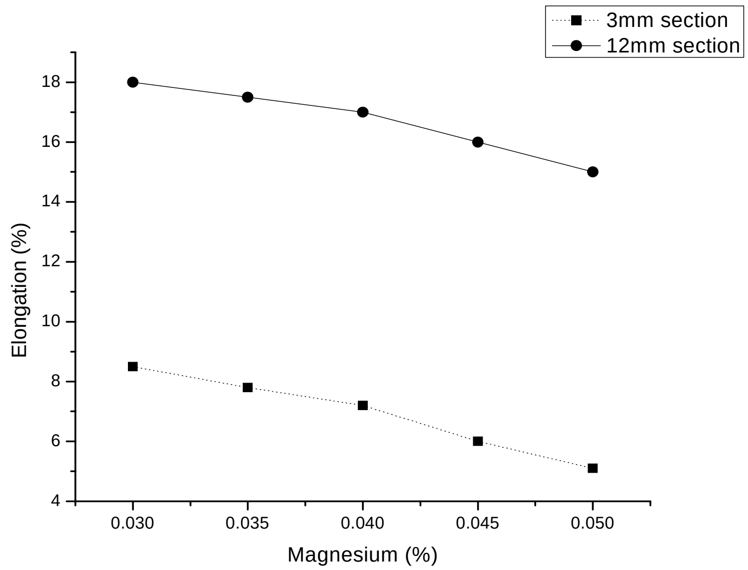


Fig.12b, Effect of magnesium on elongation of 3 & 12mm sections

(D) Effect of Cerium:

Cerium not combined with sulphur in cast iron is a powerful carbide stabilizer, and so, for any given section size, there is an upper limit of cerium which must not be exceeded if white iron structures are to be avoided. The increase in cerium content shows a small increase in the elongation of both 3 and 12 mm sections as a result of increase in nodule count and thus ferrite content (Fig. 13a).

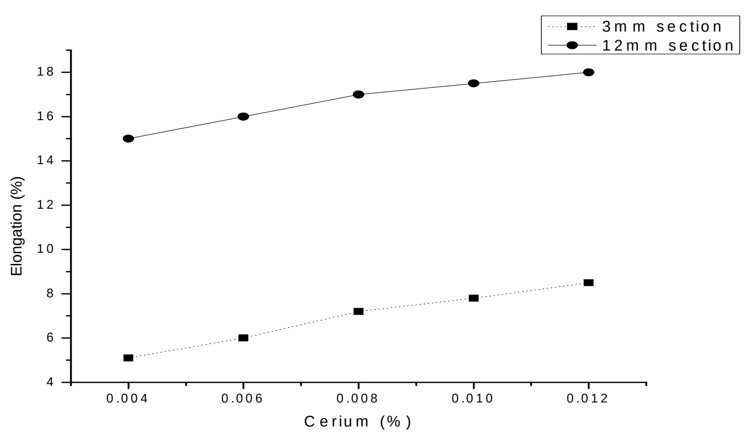


Fig. 13a, Effect of cerium on elongation of 3 &12mm sections

(E) Effect of Copper:

The chemical composition of melts number M-6 to M-10 is given in table number-6(a&b). It is found that copper can have a pearlite promoter role only when combined with a low addition of manganese. An increase in copper content shows a decrease in ductility, but yield strength and tensile strength increases for both 3 and 12 mm sections (as shown in figure13b, 13c and 13d) as a result of pearlite content in the matrix.

Table: 6a (Result of 12mm sections)

Melt No.	C%	Si%	Mn%	S%	P%	Cu%	UTS (Mpa)	0.2%YS (Mpa)	EL%	Hardness (BHN)
M-6	3.62	2.10	0.22	0.011	0.025	0.10	600.2	505	7.12	150
M-7	3.60	2.20	0.19	0.010	0.023	0.20	620.1	535.2	6.82	165
M-8	3.58	2.30	0.20	0.008	0.027	0.30	632.2	566.4	6.34	180
M-9	3.60	2.40	0.21	0.009	0.021	0.40	680.4	584.5	5.15	200
M10	3.57	2.50	0.17	0.011	0.024	0.50	700.2	596.2	4.66	220

Table: 6b (Result of 3mm sections)

Melt No.	C%	Si%	Mn%	S%	P%	Cu%	UTS (Mpa)	0.2%YS (Mpa)	EL%	Hardness (BHN)
M-6	3.62	2.10	0.22	0.011	0.025	0.10	510	425	7.12	120
M-7	3.60	2.20	0.19	0.010	0.023	0.20	530.1	445.2	6.82	135
M-8	3.58	2.30	0.20	0.008	0.027	0.30	550.2	466.4	6.34	150
M-9	3.60	2.40	0.21	0.009	0.021	0.40	565.4	484.5	5.15	165
M10	3.57	2.50	0.17	0.011	0.024	0.50	580.2	500.2	4.66	180

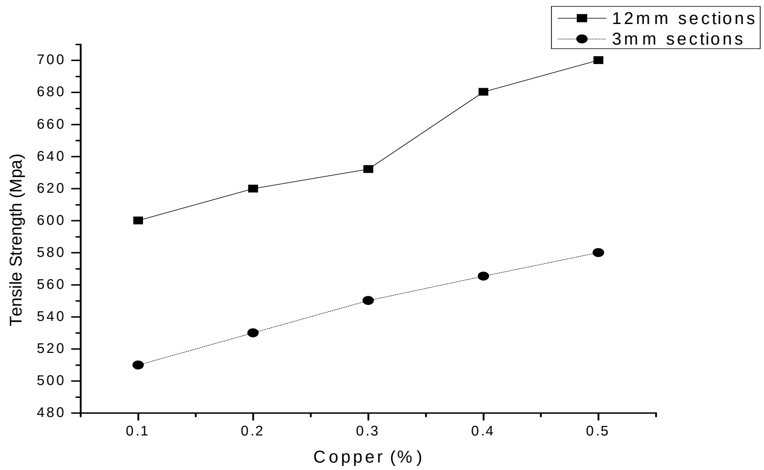


Fig.13b, Effect of copper on Tensile strength of 3 & 12mm sections

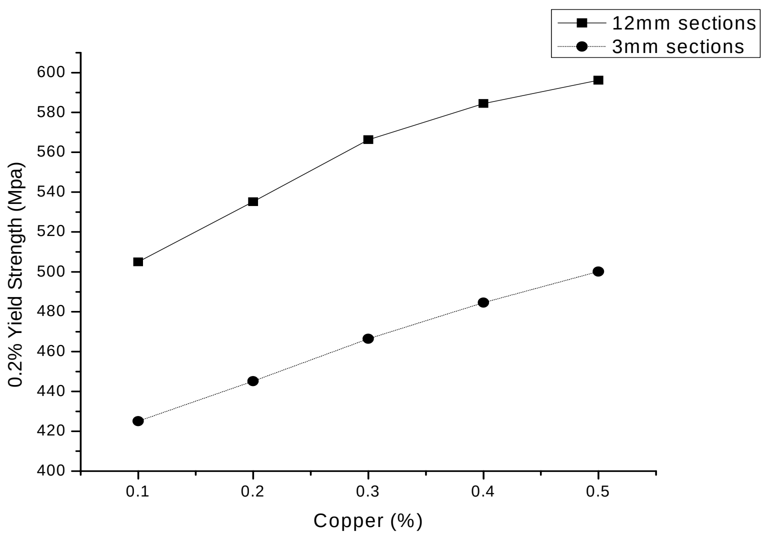


Fig. 13c, Effect of copper on yield strength of 3 & 12mm sections

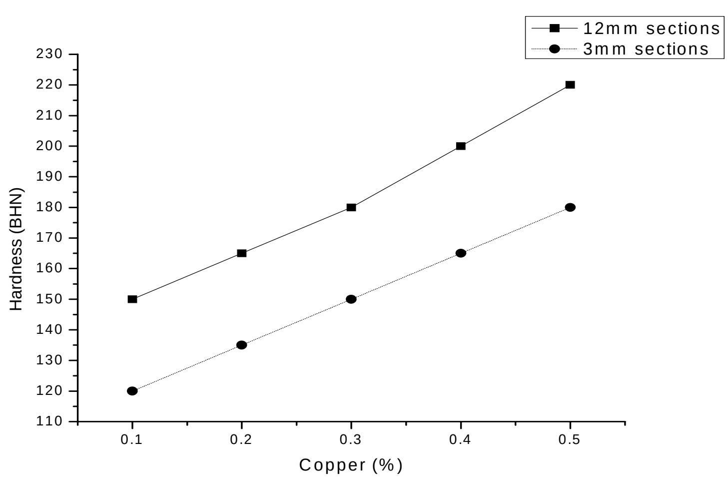
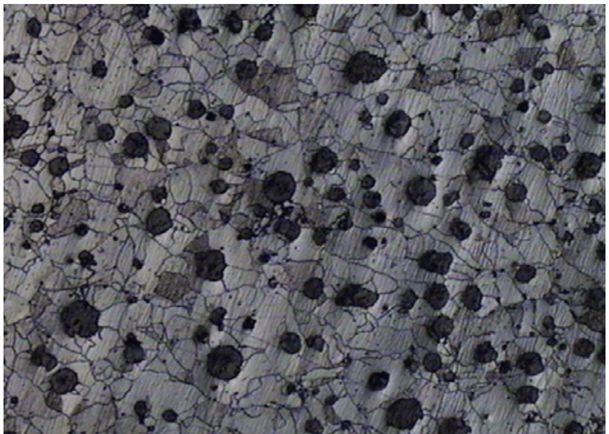
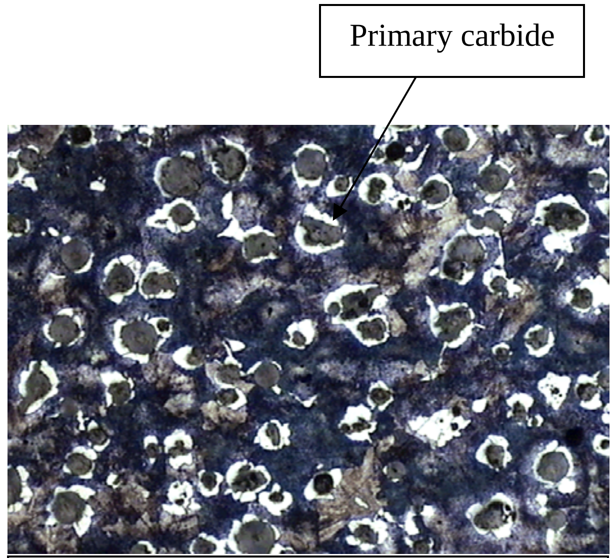


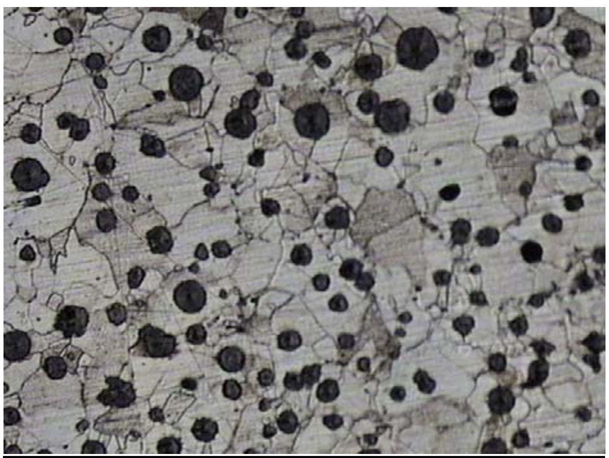
Fig. 13d, Effect of copper on hardness of 3 & 12 mm sections



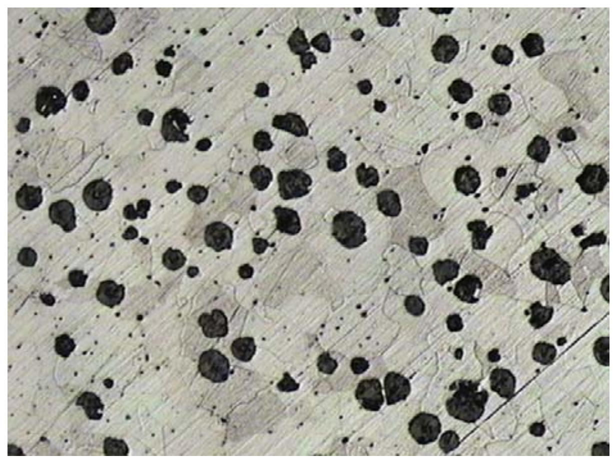
Microstructure of 12mm section
Melt no: M-4, 2% Nital etched.
Ndularity: 92%



Microstructure of 3mm section
Melt no: M-4, 2% Nital etched.
Ndularity: 75%



Microstructure of 12mm section, showing pearlite content
Melt no: M-9, 2% Nital etched.
Ndularity: 95%



Microstructure of 3mm section
Melt no: M-9, 2% Nital etched.
Ndularity: 80%

8.1 Effect of Chemical composition on Impact Properties:

The V-Notched charpy impact energies of all melts were determined as described in the experimental procedure. The effect of chemical composition on impact properties was studied and described below.

(A) Effect of Carbon Equivalent (CE):

The effect of the CE on the impact energies of 3 and 12 mm sections is shown in Fig. 14a. The impact energies of 12 mm sections decrease with an increase in CE, whereas the 3 mm sections do not show much effect. Fig. 14b shows a similar effect of carbon on impact energies. The datas are given in table-7a. For this effect melt no M-1 to M-5 was taken into consideration.

Table: 7a (Avg. impact result of 3 & 12mm sections)

Melt no.	CE (%)	C (%)	Avg.impact energy(J),12mm sections	Avg.impact energy(J),3mm sections
M-1	4.18	3.50	14.2	8.30
M-2	4.26	3.55	13.5	8.40
M-3	4.35	3.60	13.2	8.50
M-4	4.43	3.65	12.8	8.60
M-5	4.52	3.70	12.5	8.80

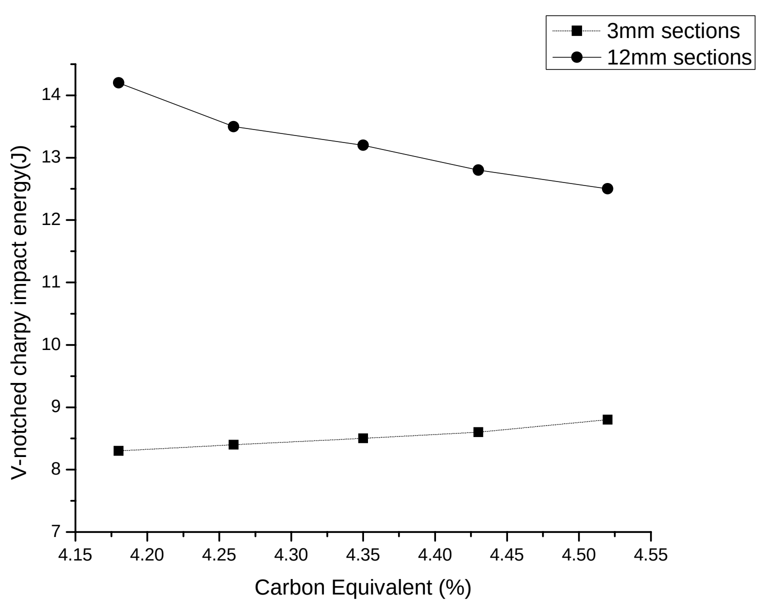


Fig. 14a, Effect of CE on Impact Energy of 3 & 12mm sections

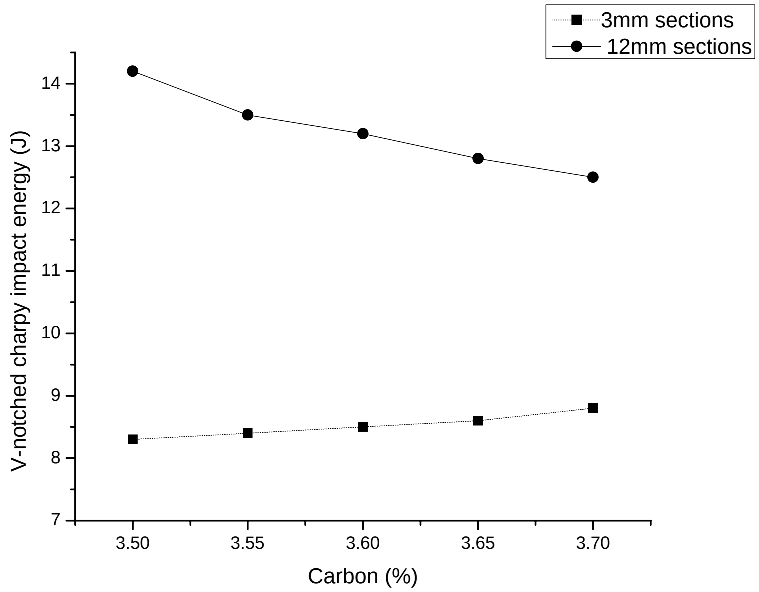


Fig. 14b, Effect of carbon on impact energy of 3 & 12mm sections

(B) Effect of Silicon:

The effect of silicon on V-notched charpy impact energies for 3 & 12 mm sections was studied from melt no M-6 to M-10 as shown in figure 15a and the data given in table 7b. Silicon shows a strong effect on the impact energies of 12 mm sections, while the 3 mm sections show a much smaller effect.

Table: 7b (Avg. impact energy of M-6 to M-10)

Melt no	Si (%)	Cu (%)	Avg.impact energy(J),12mm sections	Avg.impact energy(J),3mm sections
M-6	2.10	0.10	9.20	5.20
M-7	2.20	0.20	7.30	5.00
M-8	2.30	0.30	6.40	4.90
M-9	2.40	0.40	5.20	4.80
M-10	2.50	0.50	4.50	4.60

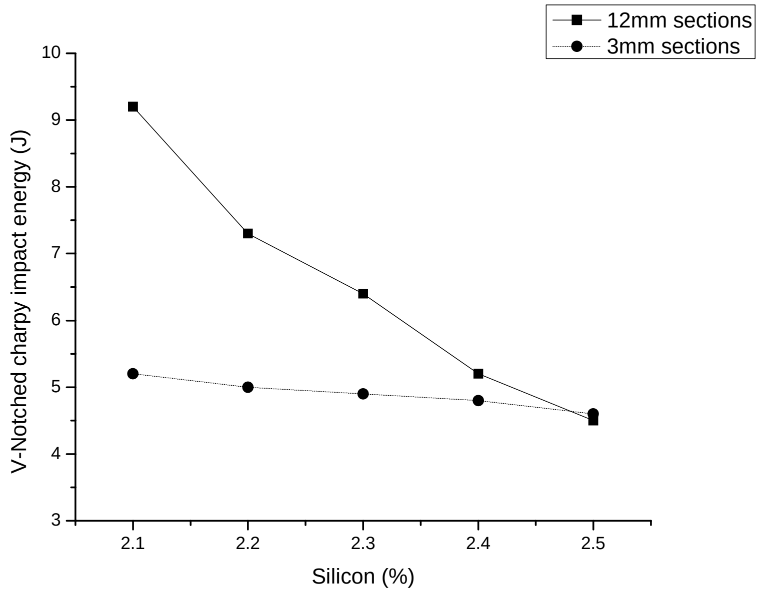


Fig.15a, Effect of silicon on impact energy of 3 & 12mm sections

(C) Effect of Copper:

The effect of copper on V-notched charpy impact energies for 3 and 12mm sections was studied for the melt no M-2, M-6 and M-7 as shown in figure 15b.

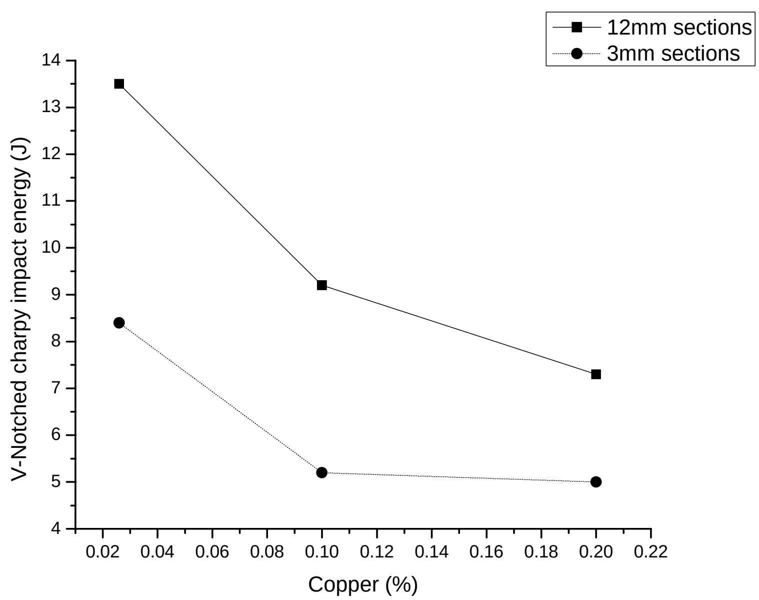


Fig. 15b, Effect of copper on impact energy of 3 & 12mm sections

The influence of copper is complex and depends upon whether the iron contains subversive elements such as titanium , in which case even as little as 1 percent copper can cause the formation of substantial amounts of flake graphite.

An increase in the cerium content produces an improvement in the impact properties of both the 3 and 12 mm sections. This might be as a result of an increase in the nodule count with the addition of cerium, which promotes ferrite. The increase in Mg content results in a slight decrease in the impact values of 12 mm sections but the 3 mm sections are not much affected by changes in Mg. The small variations in Mn and S content have no effect on the impact properties. On the other hand, the presences of certain residual elements such as Cr and Al, even in very small ranges, show a significant effect on the impact properties of 12 mm sections but no effect in 3 mm sections.

8.2 Effect of Processing Variables on Tensile Properties:

Processing Variables are mainly of pouring temperature, pre-conditioning of base iron, inoculation practice and molding materials used. As studied from the experiment, processing variables influences the tensile properties of 3 & 12mm sections as described hereunder.

(A) Effect of Pouring Temperature:

The pouring temperature of melt no M-1 to M-5 was measured and the effect of pouring temperature on ductility of both 3 and 12 mm sections was determined as shown in figure 16a and the result given in table-8a. An increase in the pouring temperature shows some improvement in the elongation of 12 mm sections but the elongation in 3 mm sections and strength in 3 and 12 mm sections does not show much more effect.

Table: 8a (Pouring temp. & EL% of 3 &12mm sections for M-1 to M-5)

Melt no.	Pouring Temperature (^oC)	Elongation (%), 3mm sections	Elongation (%), 12mm sections
M-1	1380	5.10	15.0
M-2	1400	6.00	16.0
M-3	1420	7.20	17.0
M-4	1440	7.80	17.5
M-5	1460	8.50	18.0

The initial melting was monitored and controlled in order to maintain in constant superheat from melt to melt. For if there are melt down temperature variations then the unknown inoculants and impurities which are present in all melts can interact in a variable fashion with other impurities reacted from the atmosphere or from the ladle lining to produce variable cast structure.

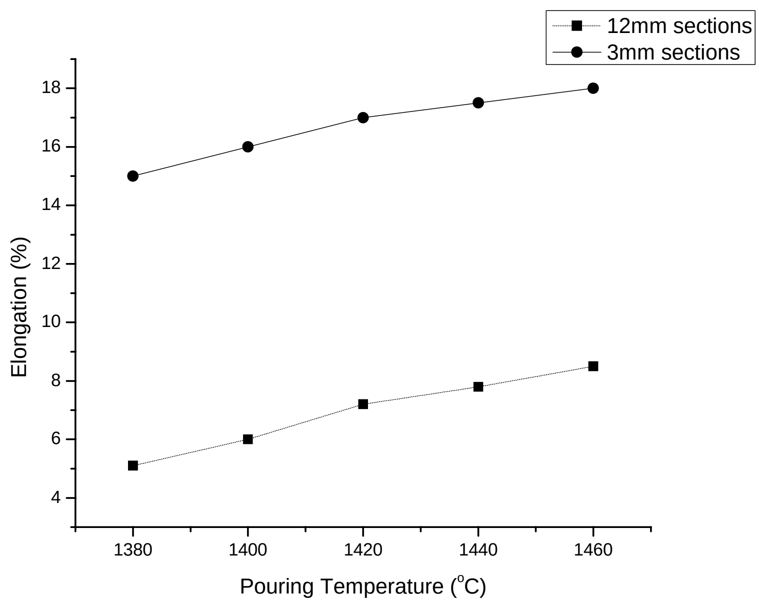


Fig. 16a, Effect of Pouring temp. on elongation of 3 & 12mm sections

(B) Effect of Pre-Conditioning of base-iron:

The process of pre-conditioning of base iron was carried out carefully during melting and casting. This process was done for melt number M-1,M-4 and M-5 by the addition of 0.20% FeSi (75%), 0.20% SiC, or 0.1%FeSi+0.1%SiC, immediately before tapping. No-preconditioning was done for M-1; pre-conditioning was carried out with adding only 75%FeSi foundry grade for M-4. Similarly pre-conditioning was carried out with adding SiC and 75%FeSi for M-5. As studied from the experiment, Pre-conditioning increases the nucleation potential, and so minimizes the potential for primary carbide formation in the final iron and improves the elongation, as shown in Fig. 16b.

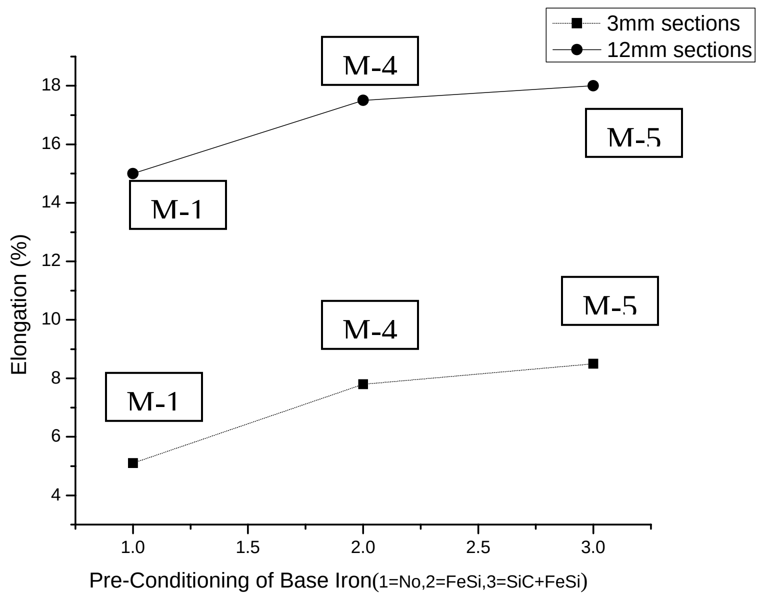


Fig. 16b, Effect of Preconditioning on Elongation of 3 & 12mm sections

(C) Effect of Inoculation Practice:

Late inoculation provides nucleation centers for nodular graphite precipitation. By so doing it promotes smaller, more uniformly dispersed and shaped graphite nodules. It increases graphite nodule count, thus minimizing the formation of primary carbides (as especially in case of thin-wall ductile iron castings) and subsequent poorly shaped nodules. The greater nodule count means that less carbon is present in the combined form, and therefore there will be more ferrite in the as-cast ductile iron castings. As a result, the as-cast ductile iron will have the optimum mechanical properties for the particular matrix structure involved. Since inoculation is a key for the structural control of ductile iron castings, the present investigation was carried out by taking two methods of inoculation practice. In-stream inoculation experiment was done for melt number M-

11 (by using 1% of 75%FeSi), M-12(by using 1% of 75%FeSi and rare earth) and M-13 (by using 1% of 75%FeSi+rare earth+bismuth). Similarly post-inoculation experiment was carried for melt number M-14(by adding 1% of 75%FeSi in the metal stream during transfer of metal from induction furnace to pouring ladle) and M-15(by adding 1% of 75%FeSi in three different stages. In first stage 0.2% was added during tapping, in second stage 0.3% was previously covered by bundle scrap in the tundish ladle for the Mg treatment and rest 0.5% was added in the tundish ladle with stirring after Mg treatment and right before pouring the castings). The result shows the beneficial effect of post-inoculation on the elongation and tensile strength of 3 and 12mm sections in figure 17(a,b&c) and the data given in table 8(b&c).

Table: 8b (Chemical Composition of M-11 to M-15)

Melt no	C%	Si%	Mn%	S%	P%	Mg%
M-11	3.48	2.04	0.20	0.010	0.022	0.041
M-12	3.50	2.02	0.19	0.009	0.023	0.040
M-13	3.52	2.05	0.18	0.012	0.025	0.042
M-14	3.54	2.06	0.22	0.011	0.024	0.044
M-15	3.51	2.04	0.23	0.008	0.022	0.043

Table: 8c (Physical Properties of M-11 to M-15)

Melt no	EL% 3mm sec.	EL% 12mm sec.	UTS(Mpa) 3mm sec.	UTS(Mpa) 12mm sec.	0.2%YS (Mpa) 3mm sec.	0.2%YS (Mpa) 12mm sec.
M-11	6.5	15.4	446.6	575.2	310.5	390.5
M-12	7.2	16.8	455.3	585.4	321.2	400.2
M-13	7.8	17.5	463.5	605.3	335.5	415.4
M-14	8.1	20.4	471.2	620.2	348.9	430.9
M-15	8.5	22.5	485.4	658.5	365.5	449.5

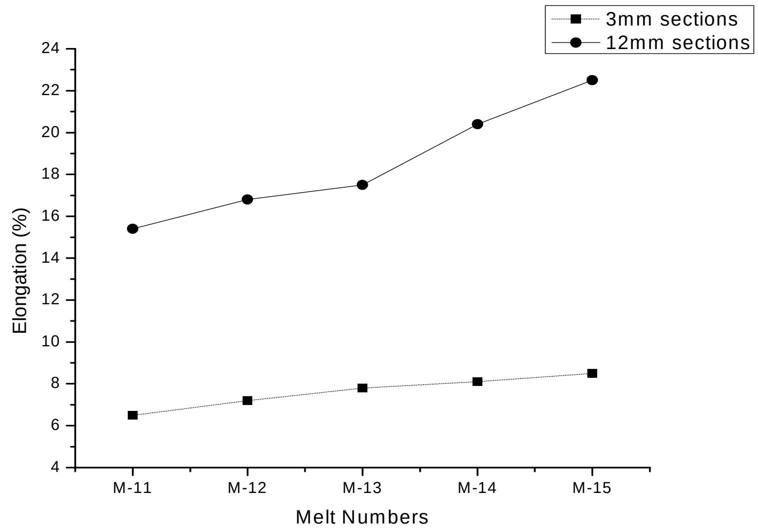


Fig. 17a, melt nos. vs. Elongation of 3 & 12mm sections

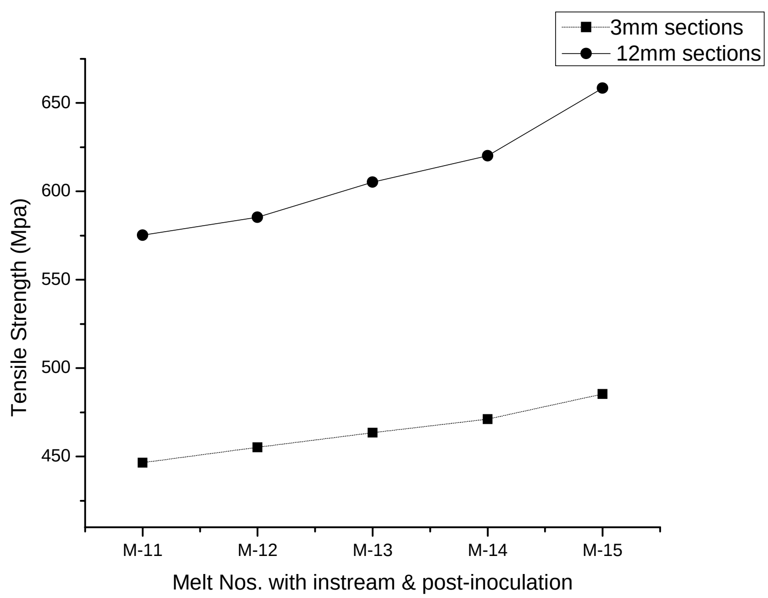


Fig. 17b, Melts nos. vs. Elongation of 3 & 12mm sections

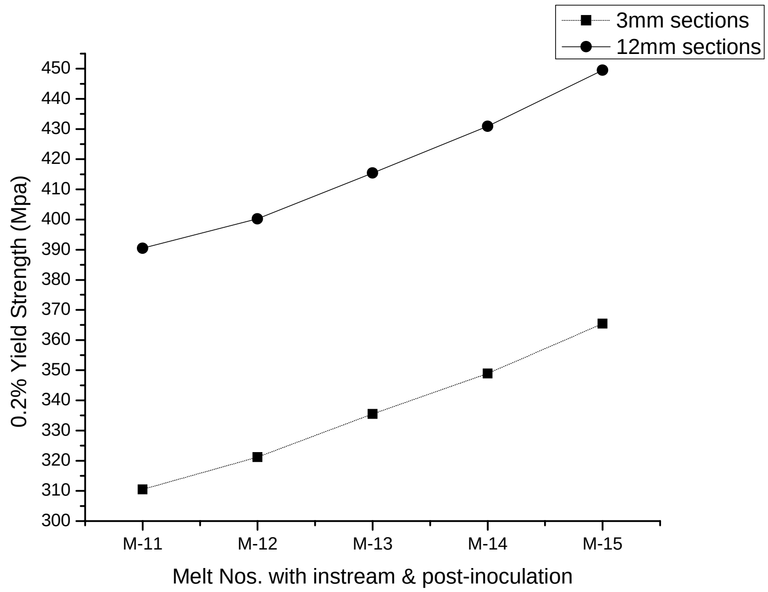


Fig. 17c, Melts nos. vs. Yield Strength of 3 & 12 mm sections

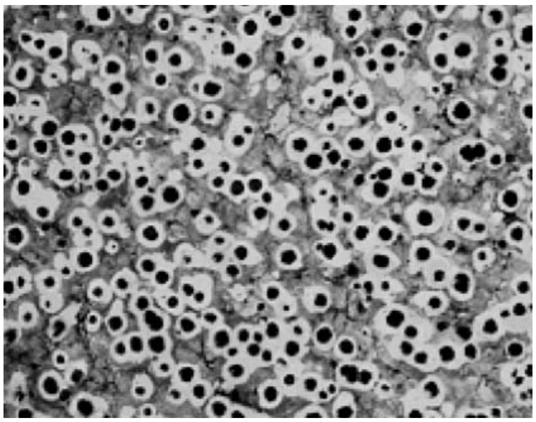
(D) Effect of Molding Materials:

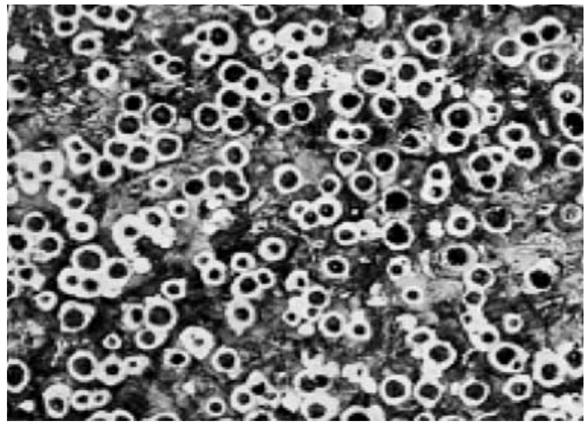
The molding materials used for the experiment is completely described in experimental procedure(chapter-7).For getting desired mold hardness and mold strength, furan resign sand was taken for mold preparation. The combination of fresh sand and reclaimed sand with resin and catalyst giving rise to better compressive strength as mentioned in chapter-7 which in result creates no defects in step bar specimens. If the step bars having defects like dross, shrinkage and inclusion then desired properties will not be obtained. Again if the sand (fresh and reclaimed) contains high sulphur then it creates dross in the casting. Hence molding materials has significant effect in the production of ductile iron castings.

8.4 Effect of Processing Variables on Impact Properties:

Pre-conditioning of the base iron and late-inoculation shows a slight improvement in the impact values of 12 mm sections but does not show any effect in 3 mm sections. Inoculant type and method of addition of inoculant has a significant effect on the impact properties of 12 mm sections but no effect in 3 mm sections. The impact energies of both 3 and 12 mm sections are not affected by changes in pouring temperature.

A direct comparison between impact values could not be made due to different test specimen sizes, but it is clear that toughness in the two section sizes was roughly equivalent when account was made for the total cross sectional area. The main difference between the Impact properties in the two section sizes lay in the relative insensitivity of the thin-section specimens to either melt chemistry or molten metal processing variables.





(3mm section, 2% nital etched, 100X) (12mm sections, 2% nital etched, 100X)
[Microstructure from the fractured end of 3 mm and 12 mm impact specimens of melt M-15]

Chapter 9

Conclusions

Ductile iron is characterized by having all of its graphite in the form of microscopic spheroids. Although this graphite constitutes about 10% by volume of ductile iron, its compact spherical shape minimizes the effect on mechanical properties. The graphite in commercially produced ductile iron is not always in perfect spheres. It can occur in a somewhat irregular form, but if it is still chunky as Type II in ASTM Standard A247, the properties of the iron will be similar to cast iron with spheroidal graphite. Of course, further degradation can influence mechanical properties. The shape of the graphite is established when the metal solidifies, and it cannot be changed in any way except by remelting the metal.

All the mechanical properties of the present investigation are compared with quality base line of ASTM A536 specifications. The conclusions could be drawn from the analysis.

- The increase in nodule count from 600 to 1500 Nod/mm^2 promotes higher metal loss. Metal loss increases with strain hardening for all the experimental conditions tested.
- Section size is the main factor influencing tensile properties of ductile irons.
- The main difference between the impact properties in the two section sizes lies in the relative intensity of the thin section specimen to either melt chemistry or molten metal processing variables.
- Silicon has the greatest effect on the tensile properties of the thin wall sections but has little effect on impact toughness.
- Production of nodular graphite structures by the process described in this experiment may represents a good understanding in the field of the metallurgy of cast iron.
- Copper has the greatest effect on the tensile properties of thin wall sections but has little effect on impact properties as observed in the experiment. Introduction of copper in high amount produces adverse effect on the mechanical properties, but by using copper-magnesium-cerium alloys this danger will be avoided.
- Processing variables (pre-conditioning of base iron, inoculation practice and pouring temperature) lead to an increase in nodule count which results in greater ductility, lower strength and improved toughness.
- The inoculation technique is of indispensable for commercial utility.

- Addition of small amount of cerium has produced a marked improvement in the tensile strength of both the sections due to replacement of a mixed flake and nodular graphite structure by a completely nodular graphite structure.
- Graphite nodules are generally finer in the thinnest sections.
- Number of graphite nodules increases as the castings thickness decreases. It exceeds2000nodules per mm^2 in the thinnest sections.
- Nodularity is generally above 80% in both the sections i.e. 3mm sections and 12mm sections.
- Presence of trace elements like copper, arsenic, antimony, bismuth, lead, indium, tin and thallium promoted the formation of pearlite in the as-cast structure as studied from melt chemistry and microstructure analysis.
- The elongation is improved with the addition of rare earth content up to 0.03% in ductile iron castings however the nodule count decreases with increase in section size.
- In order to achieve the desired physical properties it is recommended to have the chemical composition as follows.

C%	**Si%**	**Mn%**	**S%**	**P%**	**Cr%**	**Ni%**	**Cu%**	**Mg%**
3.55	2.15	0.20	0.009	0.025	0.04	0.03	0.45	0.040

- In fact, reduction in the thickness of the castings leads to an increase in strength but a decrease in ductility as the nodularity decreases with increasing solidification time.
- The nodularity of graphite nodules is improved due to the addition of RE (rare earth elements) and the amount of ferrite was observed to depend on RE and sample thickness. The addition of RE leads to a higher amount of ferrite than that of the specimens without RE. The ferrite content was found to be the lowest for the 3mm specimen with 0.02% RE.
- A direct comparison between Charpy impact values could not be made due to possible intrinsic effects associated with specimen size, but it is clear that toughness in the two section sizes is roughly equivalent when account is made for the total cross sectional area.

- Microstructure of ductile iron step bar castings with section thickness of 3 and 12mm were characterized quantitatively. The observations can be summarized as (a) pearlitic content increases with decreasing thickness of the castings. (b) number of graphite nodules increases as the casting thickness decreases. It exceeds 2000 Nod/mm^2 in the thinnest sections. (c) Graphite nodules are generally finer in the thinnest sections.
- The late-inoculation process introduced in the present investigation produces nucleation centers for nodular graphite precipitation more effectively than the in-stream inoculation process.

Chapter 10

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